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THE STRUCTURAL AND TECTONIC HISTORY OF INDIA

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THE STRUCTURAL AND TECTONIC HISTORY OF INDIA.*

By M. S. Krishnan, Ph.D., F.N.I.,

Director, Geological Survey of India (with Plates 1 to 4).

INTRODUCTION

For geological studies, India (for the sake of brevity, 'India' is used here to include India and Pakistan) is appropriately divided into two units, one being peninsular India and the other the mountain girdle of the Himalayan, the Baluchistan and Burmese arcs. The two are separated by a deep, alluvium-filled depression through which the Indus, Ganges and Brahmaputra rivers flow on the Peninsular side of the mountains. The above statement requires a little modification in that the edges of the peninsular mass are found to extend well into the region of the Lesser Himalayas (*i.e.*, between the foot-hills and the central range of high peaks) where they are inextricably mixed with the rocks of the extra-Peninsular regions.

The Peninsula is a stable mass of Archaean and Pre-Cambrian formations which are exposed over more than half its area. The rest is occupied by Gondwana and later sediments and by the lava flows of the Deccan Trap formation. The major mountain building disturbances ceased in Pre-Vindhyan (Pre-Cambrian) times. Some minor folding, block faulting (possibly block uplift and down-faulting) and epeirogenic movements have affected it in post-Cambrian epochs. Block faulting has been responsible for the preservation of India's chief coalfields, while epeirogenic movements are attested by the marine transgressions and regressions which have left their marks in the coastal regions.

The mountainous extra-Peninsular area, on the other hand, has been subjected to stupendous mountain building activity in the Cretaceous, Tertiary and Pleistocene times. It shows a complete succession of sedimentary rocks of all ages from the Cambrian to the Pleistocene,

* This is a revised and enlarged version of a short paper entitled "The Structure of India" published in the *Indian Geographical Journal* (Madras), Vol. XVIII, No. 4, pp. 137-165, 1943.

deposited in a great basin of geosynclinal dimensions bordering India on the north. This region is perhaps best described as the meeting ground of two continental masses—India from the south and Asia from the north. The cores of the uplifted mountains show large scale intrusions of plutonic rocks, mainly of granitic composition, but also some basic and ultrabasic rocks in places. Only parts of the mountainous area have been mapped and there remain large gaps to be filled up. The mountain belts are characterised by complex folding, overthrusts and 'nappes' of great dimensions, involving horizontal compression of the crust of several hundred miles. Each of the three major arcs making up this region has its convex side facing the stable mass of the Peninsula, so that the thrusts are directed towards the south in the Himalayas, towards the east in the Baluchistan arc and towards the west in the Burmese arc. Each of these arcs consists of a succession of mountain ranges one behind the other and, in a few places, they are gathered up by the underlying wedges of the Peninsular mass into a series of festoons, so conspicuously seen in the Baluchistan arc. Intrusive plutonic rocks are present in all the arcs but the details about their distribution are still wanting as there are several areas, especially in the Himalayas and in the mountains of the Assam-Burma border, about which geological information is scanty or entirely lacking.

As the stratigraphic and tectonic histories of the two regions are different, it would be best to treat them separately until the Tertiary, when they encroached on and influenced each other.

THE PENINSULA

I. The Archaean Formations

More than half the area of the Peninsula exposes Archaean gneisses and schists and Pre-Cambrian sediments and igneous rocks which have been metamorphosed to various degrees. The earlier rocks were probably largely of igneous origin, penetrated intimately by granitic intrusives, giving rise to banded and composite gneisses. The original volcanic flows and tuffs and sedimentary rocks have been converted into amphibolites and various types of schists. Three periods of granitic intrusion have been recognised and it is not unlikely that more will come to light when more detailed studies are undertaken in different regions. The earliest of these is generally a highly folded gneissic complex for which the term 'Peninsular Gneiss' has been used in South India (Smeeth, 1916). The next appears to be a porphyritic or augen gneiss (in the Central Provinces), while the third is a granite which is to a large extent unaffected by folding and is of Upper Pre-Cambrian age—the Closepet granite of Mysore, the Arcot and Hosur granite of Madras, the Erinpura granite of Rajputana, the Singhbhum granite of Bihar, etc.

The highly metamorphosed and schistose Pre-Cambrians are known by different names in different parts of the country — the Dharwars in South India, Champaners and Aravallis in Gujarat and Rajputana, the Sausars and Sakolis in the Central Provinces, Shillong series in Assam, Bengal gneiss in Bihar, Darjeeling and Daling series in Sikkim, and so on.

The earlier gneisses are intruded by the charnockites (hypersthene granulites) which are well developed, especially all along the Eastern Ghats up to the Nilgiri mountains and along the Western Ghats from Coorg to the southern tip of the Peninsula. They are pre-granite in age and presumably pre-Cuddapah (pre-Algonkian) as they show evidence of having been folded, in many places. They generally exhibit the characteristics of igneous intrusives as pointed out by T. H. Holland (1900) and are associated with pegmatitic phases. The larger masses are acid to intermediate in composition, but in certain areas there are ultrabasic members composed mostly or entirely of enstatite-hypersthene. In the Eastern Ghats of Jeypore in Orissa, they show evidences of later albitisation (Crookshank, 1938). Gneissic banding and folding are common in the major exposures of the Eastern Ghats, Palni and Nilgiri hills, etc. The charnockites are now generally considered to be an igneous suite which has been subjected to high-grade plutonic metamorphism, with the development of hypersthene which is their most characteristic femic mineral. Augite (often titaniferous) and garnet are commonly found, while minerals with hydroxyl molecules like amphibole are comparatively rare and often absent. The distinctly bluish colour of the quartz (and even of the feldspar) is generally attributed to the presence of minute rod-like inclusions of rutile, but may really be due to some other cause. Whatever their origin, whether entirely igneous or derived from a variety of pre-existing rocks as held by

Vredenburg (1918) and B. Rama Rao (1945), it is clear that they have undergone severe metamorphism under conditions of the kata-zone. The recent discovery of workable chromite deposits in such rocks in the Kondapalle Hills near Bezwada in the Kistna Valley gives rise to the speculation that they may consist, in part, of material which may have risen up from the peridotite shell of the earth, especially as the charnockites appear to be associated with folded mountain belt of the Eastern Ghats. The charnockite areas have not been studied in sufficient detail for us to be able to say whether the ultrabasic members are intrusive into the intermediate and acid members or whether they are merely differentiates from a common magma.

2. Trend Lines in the Archaeans

There are certain persistent regional trends noticeable in the Archaean

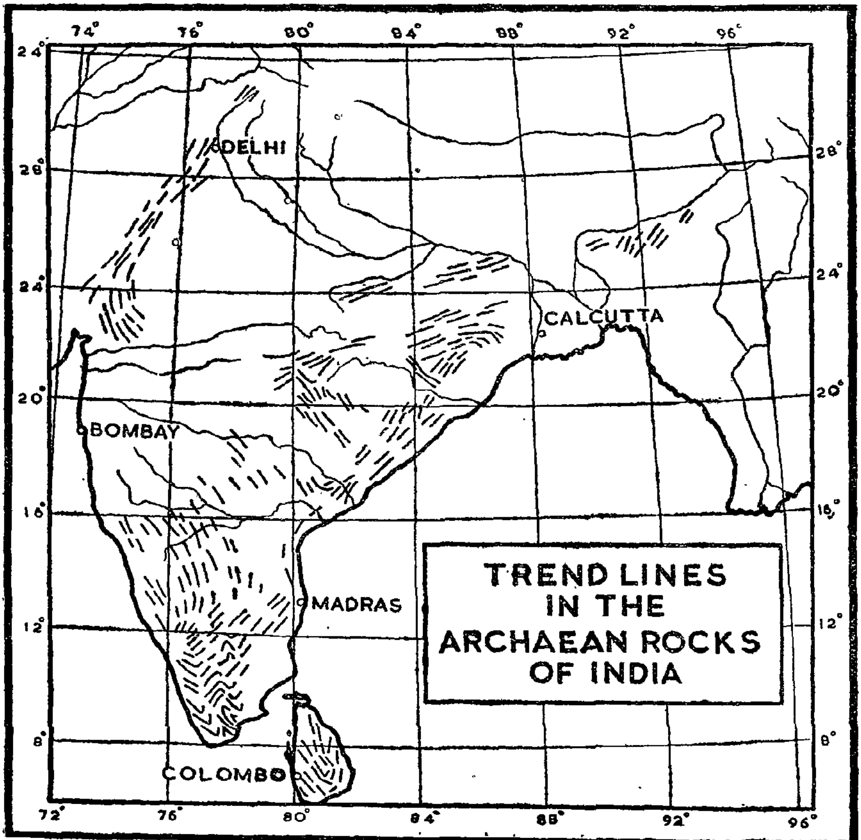

Fig. 1.

rocks of the different parts of India, which are described below (see also Fig. 1).

The Aravalli strike.—The Aravalli mountain belt of Rajputana is characterised by a N.E.-S.W. strike which can be seen from Delhi to Champaner in Gujarat at the head of the Gulf of Cambay. In the Gujarat region it tends to splay out rather widely and a part of it, if continued, is directed towards Mysore in South India where the Dharwarian rocks have a dominant N.N.W.-S.S.E. strike. Though the area intervening between Gujarat and Mysore is covered by the Deccan Trap lavas, there appears to be little doubt about the direct connection between the Archaeans of the two areas. Still further east in Gujarat, the Aravalli trend seems to turn south-east and east. In the absence of detailed studies in this critical region, it is not possible to say whether the Aravalli trend gradually turns round and merges into the Satpura strike (see below) or whether the apparent turning is merely due to the interaction between two independent trends, one superimposed on the other.

The Aravalli strike is found to continue into Garhwal in some of the older rocks (Auden, 1933, p. 467). It may be that there was a rejuvenation of the northern part of the Aravallis in Tertiary or post-Tertiary times, but on this point there is no clear evidence. However, the rocks referred to above have retained their original strike unaffected by the Tertiary orogenic movements, probably because the movements were parallel to this strike direction. Detailed studies of the post-Archaean formations in this region will bring to light facts which will explain their distribution in relation to the Aravallis (Fermor, 1930, p. 391).

The Aravalli-Champaner trend apparently continues to the south into the Laccadives through the Banks in the Gulf of Cambay and the Direction and Angria Banks further south. The Laccadive, Maldive and Chagos island groups lie along this alignment and all of them rise up from platforms 1,800 to 2,000 fathoms deep, as pointed out by Sewell (1935) who quotes the opinion of Moresby who surveyed this region in 1834 to 1836. G. Schott (1902, p. 117) was also of the opinion that the Maldives and the Chagos groups stand on parts of a single platform at the bottom of the sea. There is a breach in the continuity of the Aravallis in the Cambay-Gujarat region where transverse faults have let down a portion, probably in Upper Carboniferous times, while the western coast of India was faulted down in the Miocene. Little is known regarding the subsurface geology of the abovementioned island groups but their tops are built up of coral reefs which continue to grow at the present day. If the southward extension of the Aravallis into these island groups is accepted, their length in the submerged portion to the south of Champaner would amount to about 1,500 miles.

The Dharwarian strike.—As mentioned above, a part of the Aravallis in Gujarat trends in a SSE direction and apparently continues under the Deccan Traps into Mysore and adjacent parts of Hyderabad and Madras where the general trend is NNW-SSE to NW-SE. In the south of Mysore, near Mysore City and further south, the same rocks exhibit a high degree of metamorphism and assume a N-S strike, and finally

turn SW and WSW, thus adjusting their trend to that of the Eastern Ghats of Salem and the Nilgiris.

Wadia (1943) has identified three peneplanes—post-Archaean, post-Jurassic and Tertiary—in Ceylon which is geologically a part of Southern India. He believes (1942) that this holds for South India also where the charnockite massifs stand out, bounded by steep scarps, above the general level of the Mysore plateau and other hills to the south. Lower down are the general plains which grade into the coastal regions. The Nilgiri mountains are regarded by him as elevated to their present height by a Tertiary uplift.

In the region south and south-east of the Nilgiris the dominant strike is NW-SE, which continues into the south-western part of Ceylon. There is a great similarity between this (southernmost) part of South India, Ceylon and Madagascar in the rocks they contain and in the associated minerals—garnet, sillimanite, graphite, monazite, thorianite, ilmenite, zircon, etc.—so that the belief that they were all originally parts of a single land mass is greatly strengthened. There is indisputable evidence that Ceylon was connected to India until the Miocene and occasionally thereafter. The NW-SE strike of the southernmost part of India may or may not be part of the Dharwarian strike and a satisfactory decision of this question must await detailed structural studies of critical areas here.

The Eastern Ghats strike.—Parts of the Nilgiris and of the districts of Coimbatore and Salem to their east and north-east, exhibit an ENE-WSW strike. In South Malabar to the west of Nilgiris, NNW-SSE and N-S strikes are seen but some feldspathic schists further west show, according to Lake (1890, p. 12), an E-W strike of foliation. This latter foliation generally bends round the rocks which show the N-S strike. The feldspathic schists and their foliation therefore appear to be younger than the 'quartzose gneisses' having the Dharwarian strike (Oldham, 1893, pp. 36-37). This E-W strike may possibly be the westerly continuation of the ENE strike of the Nilgiris and may have a bearing on the presence of the Palghat gap—a conspicuous gap in the Western Ghats just south-west of the Nilgiri mountains.

Eastward of Wainad (the tract adjoining the Nilgiris on their north-west) and the Nilgiris, the ENE-WSW strike continues for some distance, but gradually assumes a NE-SW to NNE-SSW strike which is well seen in parts of Salem and Trichinopoly. It continues towards Madras City north of which it assumes a broad sigmoidal flexure parallel to the eastern margin of the Cuddapah basin and to the Madras coast. The southern part of this margin is in fact parallel to the trend of the Dharwarian schistose rocks into which the Nellore mica-pegmatites are intrusive. From Guntur and the Kistna Valley, the strike assumes a NE direction, but curves inwards with a NNE direction near the northern border of Orissa where it is either interfered with by the Satpura strike of the Gangpur-Singhbhum region or is obscured by alluvial cover. The western part of the wide belt in northern Orissa includes the iron-

ore ranges of Keonjhar and Bonai whose dominant trend is NNE-SSW. It is not unlikely that there is a bifurcation of the Eastern Ghats belt near Bezwada in north-eastern Madras[1], one part going straight south to Ceylon and the other continuing for some distance southwards and then bending round to the south-west to proceed to the Nilgiris through Arcot and Salem.

The effect of the Eastern Ghats orogeny is seen all along the eastern margin of the Cuddapah basin in Nellore and Guntur and almost up to the Singareni coalfield in Hyderabad. The eastern margin of the Cuddapah basin shows crushing and overthrusting. Some rocks near the Singareni coalfield show folding and high grade metamorphism whereby schists with garnet, kyanite, staurolite, etc., have been produced from the argillaceous members, and crystalline limestones and calciphyres from the calcareous ones. Granitic rocks are associated with the folding. Heron (1949, pp. 118-121) correlates these rocks with the 'Pakhals' which are considered to be the equivalents of the Cuddapahs (Algonkian). Mahadevan (1949), however, believes that the relationships, structure and metamorphism of these rocks, as well of the Kaladgis of southern Bombay, indicate an earlier age, *i.e.*, Archaean, for them. He points out that though the eastern margin of the Cuddapah basin of Madras shows evidence of folding and shearing, there are no associated granitic intrusives as in the case of the 'Pakhals' of the Singareni area. The elucidation of this problem would therefore have to await the results of detailed studies of critical areas in the Nellore-Guntur-Singareni region.

Holmes (1950, p. 26) has recorded the ages calculated for samarskite obtained from the pegmatites of Nellore, which are 830, 1550, 1760 million years, on data furnished by two groups of investigators in India. The first of these is not far out from the results given by minerals from post-Delhi pegmatites of Rajputana or from the post-Satpura pegmatites of Gaya in Bihar. The other two give much higher figures, 1550—1760 million years which must indicate an Archaean (Dharwarian) age. If the results are all reliable, one would be led to conclude that there must be two sets of pegmatites here, of vastly different ages. So far as I could gather, the samarskite came from undisturbed pegmatites of the Sankara and Parlapalle mines in the Gudur area which should be assigned a post-Dharwarian and pre-Cuddapah age. It will be necessary to repeat the chemical work on carefully selected material, as there is no field evidence, to the best of my knowledge, for the existence of two sets of pegmatites separated by such a large interval of time as the above results suggest.

The Eastern Ghats consist largely of charnockites and khondalites (garnet-sillimanite gneisses and schists) with some calc-rocks and metamorphosed manganiferous sediments. Fermor is of the opinion that they constitute a belt of block uplift and that the margins are zones of faulting.

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[1] Dr. C. Mahadevan (personal communicaton) says that the bifurcation starts in the Kondapalle Hills, a few miles north-west of Bezwada.

Though, according to Crookshank (1938, pp. 399-404), no fault is discernible in the Jeypore region, Fermor's view is based on the high grade metamorphism characterising all the rocks of this belt which must have been acquired when the rocks were buried deep. Practically throughout the Eastern Ghats belt from Orissa to the Nilgiris, charnockites are conspicuously present and granitic intrusives are not wanting though they do not attain great importance.

The Mahanadi Strike.—In the area of Archaean rocks lying to the north-west of the Eastern Ghats, from the Godavari Valley to the Mahanadi Valley, the general direction of strike is NW-SE, but geological information on this region is still very poor. It will be noticed that this structural trend has controlled the formation of the block faults (' graben ') in which the Gondwana formations have been preserved in the Godavari and Mahanadi Valleys. As this trend is not very different from the Dharwarian, it is not clear whether this region is to be treated as a separate entity or as part of the Dharwarian structural province.

The Satpura Strike.—The last major trend is that of the Satpura Range with an ENE-WSW direction. The Satpura Range between the Narbada and the Tapti in Gujarat is made up of Deccan Traps and the trend is continued through the Mahadeva Hills, the Maikal Range, the Mainpat Hills and the north of the Chota Nagpur plateau to the Rajmahal region in the Ganges Valley. The Archaeans are seen mainly from Jubbulpore eastwards. There is also a southern group of conspicuous outcrops in the Nagpur-Chhindwara-Bhandara-Balaghat region of the Central Provinces and the Gangpur-Singhbhum region of Chota Nagpur, where the same strike is seen. Further east beyond the Rajmahal region which flanks the Ganges Valley, this trend is continued into the Garo Hills in the western part of the Shillong plateau, while much of the rest of the plateau shows the Eastern Ghats trend.

In Singhbhum in South Bihar, which has been mapped in recent years in detail by Dunn and others (1929, 1939, 1942), evidences of the Satpura orogeny have been studied. A major thrust zone separates the highly metamorphosed northern area from the unmetamorphosed southern area This thrust zone runs roughly ENE-WSW and E-W for nearly 100 miles turning to the S-E near the eastern end and is associated with copper mineralisation because of which it is known as the ' Singhbhum Copper Belt '. There are two nearly parallel thrust zones to its north, one marking the northern border of a belt of lavas (Dalma Traps) and the other further north. All the three are parallel to the Satpura trend and tend to converge near Goilkera, west of Chakradharpur. The thrust in all cases is from the north. To the south of the main thrust zone, the same series of rocks are practically unmetamorphosed but have been affected by the folding of the Eastern Ghats (NNE) strike. The thrust

zone is continued westwards into Gangpur through the northern border of the Gangpur anticlinorium which contains rocks thought to be older than those of Singhbhum (Krishnan, 1937).

Beyond the last thrust zone in the north, there are granite gneisses which occupy a broad belt between south and north Bihar. They become conspicuously banded and gneissic as they approach the schists in the south and are granitic in the north. During the period of (Satpura) folding, ultrabasic rocks and granite were intruded the latter being apparently the younger. A phase of the granitic intrusion consists of granophyre and soda granite chiefly intruded along the main thrust zone, the copper mineralisation along the same zone being attributed to this phase.

3. Relative Ages of the Orogenic Cycles

Attention may be drawn here to the fact that the Aravalli trend of Rajputana is parallel to that of the Eastern Ghats ; the Dharwarian and Mahanadi trends (including that of the southernmost part of the Peninsula) may really be identical. There are areas in which the different trends meet each other. Structural and petrofabric studies in such areas must yield results of much value, for instance in eastern Gujarat, the Nilgiris and Malabar, Salem-Mysore and the western margin of the Eastern Ghats. In Bhandara in the Central Provinces and in southern Gangpur in Orissa there is evidence that three different trends come together forming triangular patterns.

There are few reliable data regarding the relative ages of the major folding movements which produced the trends described above. In the Aravalli region the diastrophism was repeated in Upper Pre-Cambrian (post-Delhi) times and acid lavas, granites and pegmatites were erupted and injected at the time of the later activity also. There is some evidence in the Gangpur anticlinorium that the Satpura trend has effected an older one, presumably the Eastern Ghats trend (Krishnan, 1937, p. 73). Because of this the porphyroblasts in certain mica schists have been only partially turned and the rocks have been subjected to regressive metamorphism.

A. Holmes (1949 and 1950) has investigated the ages of uraninite from a pegmatite from Gaya in the Satpura belt of Bihar and of uraninite and monazite from post-Delhi pegmatites of the Aravalli belt in Rajputana, and found that the former indicated an age of 955$\pm$ 40 million years and the latter 735 million years. From these data he has deduced that the post-Delhi orogeny, with which the Rajputana pegmatite is associated, is younger than the Satpura orogeny which gave rise to the Gaya pegmatite. Since the Aravalli orogeny is much older than the

Delhi one, the former was thought to be the oldest of the Archaean orogenic cycles in India. The Eastern Ghats cycle was given an age intermediate between the Aravalli-Dharwar cycle on the one hand and the Satpura cycle on the other. Holmes has consequently formulated a succession of diastrophic cycles as shown below (1950, p. 27) :—

VINDHYAN

~~~~~~~~~~~~~~~~~~~~

735 m. y.

DELHI CYCLE (= ? CUDDAPAH)

~~~~~~~~~~~~~~~~~~~~

955 ± 40 m.y.

SATPURA CYCLE

~~~~~~~~~~~~~~~~~~~~

EASTERN GHATS CYCLE

~~~~~~~~~~~~~~~~~~~~

(ARAVALLI CYCLE) ?=DHARWAR CYCLE

~~~~~~~~~~~~~~~~~~~~

OLDER GNEISSIC COMPLEX (= ? BUNDELKHAND GNEISS)

In explanation Holmes wrote (1950, p. 26) :—

"For this reason it is provisionally supposed that the Aravallis and the Dharwars constitute parts of a single orogenic belt. This is an example of a tentative correlation that remains to be proved by the dating of radioactive minerals. It should be added that the Aravallis are underlain by a "Gneissic Complex" which represents a still older orogenic belt.

The relative positions of the Satpura and Dharwar rocks can be arrived at by another route. The map shows that the Eastern Ghats belt, celebrated for its khondalites, kodurites and charnockites, cuts across the Dharwar belt and therefore represents a younger orogenic cycle. The Satpura belt, however, appears to be younger still, judging from observations made in Orissa by Krishnan (1943 a, p. 141). Minerals suitable for dating the late pegmatites of the Eastern Ghats belt (more likely to belong to the Dharwar belt) occur in the pegmatites of the Nellore district, and already a few analyses of samarskite have been made for the purpose. The crude ages so far available are 830, 1550, and 1760 m.y. On balance, these also suggest that the Eastern Ghats belt is older than the Satpura belt........"
~~~~~~~~~~~~~~~~~~~~

In regard to the necessity for separating the different orogenic cycles in the Archaeans, Holmes wrote (1949, p. 299) :—

"At the moment, however, it can be concluded either that the Satpura and Eastern Ghats belts are of about the same age, or that the Eastern Ghats belt is older than the Satpura belt. The tectonic evidence strongly supports the second view. In either case, the Dharwars are older than both. Rocks of the Eastern Ghats and Satpura belts should therefore no longer be referred to as 'Dharwars' as they commonly have been in the past (Krishnan 1935; Fermor 1936, p. 214) To do so would be to perpetuate a mistake that is analogous to the misuse of the term 'Laurentian' in North America. The original Laurentian rocks of the Grenville Province have a closing age of just over 1000 m.y. (Holmes 1948 a, 180-184). The post Keewatin pegmatites of the Rainy Lake may have an age of nearly 2000 m.y. (Holmes 1948 a, 189-193). Yet the post-Keewatin granites and migmatites have been called 'Laurentian', implying an entirely unjustified correlation with rocks 800 miles away and completely unconnected. Similar mistakes have been made in all the better known Pre-Cambrian shields, and only now, with the progress of mapping and the aid of radioactive minerals is it becoming possible to disentangle the long succession of orogenic belts which make up the so-called 'Archaean' once thought to represent an era of world-wide orogenesis."

In a discussion of the data presented by Holmes, Fermor (1950) remarks that the only conclusion to be drawn from them is that the pegmatites from which the uraninite and monazite were got had an age between 700 to 900 million years and that they cannot be used as indications of the ages of the schistose rocks cut through by these pegmatites, since these schistose rocks may be many millions of years older than the pegmatites, and since the pegmatites in the same area may be of more than one age.

In reply to Fermor's criticism, Holmes has pointed out that he was attempting to date the close of the orogenic periods while Fermor was thinking of the ages of the formations in the different belts (Holmes 1950 a, p. 227).

While discussing the different tectonic trends, I have pointed out that there is some evidence of the Satpura trend in the Gangpur area being younger than another, presumably the Eastern Ghats, trend. I have also referred to Lake's work in Malabar which shows that the foliation of the feldspathic schists having E.W. strike (which is presumably hat of the Eastern Ghats strike near its termination in this region),

'flows' around the masses of quartzose gneisses having the Dharwarian trend of the Western Ghats. In the Nellore region north of Madras, where some Dharwarian rocks with the characteristic trend are present, the Eastern Ghats belt seems to mould itself on the Dharwarian as it shows an eastward convex bend and again resumes its original direction (NNE and NE) near Madras City. It may be inferred from these that the Eastern Ghats orogeny is younger than the Dharwarian. I have also pointed out above that the Eastern Ghats appear to have been affected by a later, *i.e.*, post-Cuddapah, diastrophism along the same belt. Hence, the data from age determination of pegmatite minerals do not dispose of Fermor's contention that each of the orogenic belts may contain rocks of different ages. The correlation of the formations of the different belts can be solved mainly by careful structural studies. These can, of course, derive some help from radioactive age determinations of minerals whose sources can be dated with confidence.

It is known that there is a ridge beneath the alluvium in Punjab trending in a north-westerly direction from Hissar (west of Delhi) to near the Salt Range. This rises above the alluvium only at a few places near the north-western end, in the Kirana and Sangla Hills 40 miles to the SSE of the Salt Range. These hills extend over a distance of some 60 miles in a NW-SE direction, which is also the strike of the rocks composing them. These rocks are Pre-Cambrian and are entirely different from any in the Salt Range and are more related to those of the Aravalli mountains (Heron, 1913, p. 229). Auden (1949, plate XI and p. 153) regards this ridge as a continuation of one of the western ranges of the Aravallis which would thus have a sigmoidal shape when followed from western Punjab through Rajputana to Dharwar and Mysore. This Punjab ridge, it will be noticed, is parallel to the Himalays, and is flanked on its north by a trough similar to the Gangetic trough or foredeep in Bihar, in front of the Himalayas. The structure and history of this ridge is not easy to decipher as it is entirely covered over by alluvium except for the few hills rising above the alluvium near the Salt Range.

4. The Assam Plateau and Wedge

The Assam plateau, of which the outlying Mikir hills are undoubtedly a part, consists mostly of Archaean and Pre-Cambrian rocks, overlain along the southern margin by the Sylhet traps (Jurassic) and Cretaceous and Tertiary sediments. At and near its western end the rocks of the plateau show the Satpura trend, while in much of the rest of the area the trend is that of the Eastern Ghats. Though now separated from the main peninsular area by a broad strip of the Ganges-Brahmaputra alluvium, there is no doubt that the Assam plateau is part of the Peninsular shield. It appears to have been covered by the sea from the Jurassic or Cretaceous onwards and to have experienced the effect of the Tertiary

movements of the Himalayan and Burmese arcs in that it was uplifted in the Miocene. The Himalayas are thrust towards it in a southerly direction and the mountains of the Burma border in a westerly and northwesterly direction. Fox (*see* Heron, 1937) says that the plateau is sliced by a system of faults which run N.-S., *en echelon*, each faulted slice having been shifted slightly to the south of the one immediately on its west. The Assam block continues to the north-east as a wedge, submerged under the Brahmaputra alluvium, for its influence is felt in the Sadiya region and beyond, where occurs a remarkable hair-pin bend in the strike of the Himalayan formations. This critical region is unfortunately little known geologically, but there seems to be no doubt that the Himalayan formations continue into the Burmese arc comprising the Patkoi, Manipur and Arakan mountains (Wadia, 1936). The continuity seems to be partly interrupted in the Sadiya frontier tract and Mishmi Hills which expose highly metamorphosed Archaean rocks with NW-SE strike. To the east of this, in the Hukawng Valley and Fort Hertz area. there are Archaean schistose rocks and granitic intrusives but these may possibly belong to the Burmese province. The effect of the Assam wedge is seen far to the north-east in south-eastern Tibet and south-western China. The mountain chains of that region show a sharp north eastward flexure or convexity. The great rivers of south-east Asia—the tributaries of the Brahmaputra, the Irrawaddy, the Salween, the Mekong, the Yang-tse—rise in a small tract north of Upper Assam, and after flowing some distance southward, diverge widely and flow finally into the Indian Ocean or the Pacific as the case may be.

In the western part of the southern border of the Assam plateau, the Cretaceous and Tertiary rocks are overthrust by older rocks from the north. Followed eastwards, this overthrust zone passes into a monoclinal fold whose southern limb plunges steeply into the alluvial plains below. Further to the east, the same zone takes a north-easterly direction and merges into a thrust fault—*the Haflong-Disang thrust*—but now the thrust is from the south-east, from the side of the Burmese age. This thrust marks the north-western limit of the Disang series of Eocene age.

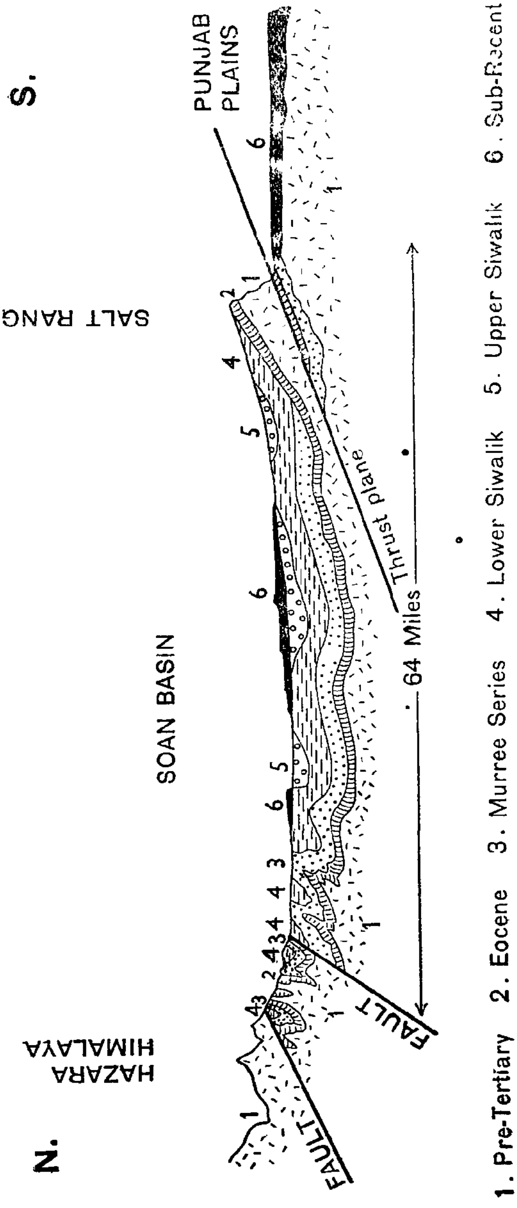
More or less parallel to, and some distance north-west of, the Haflong thrust, is another thrust fault, also directed to the north-west. This is called the *Naga thrust*. It is close to the border of the Brahmaputra alluvium in Upper Assam. Several producing oil wells have been drilled in the Tertiaries involved in the Naga thrust. Numerous other parallel strike faults and overthrusts are seen in the Naga hills to the south-east, even beyond the Haflong-Disang thrust.

The northern border of the Assam Plateau is faulted and presents a scarp towards the plains of the Brahmaputra. Like the Ganges in Bihar, this river also flows through a trough in front of the folded Himalaya mountains.

5. The Punjab-Kashmir Wedge

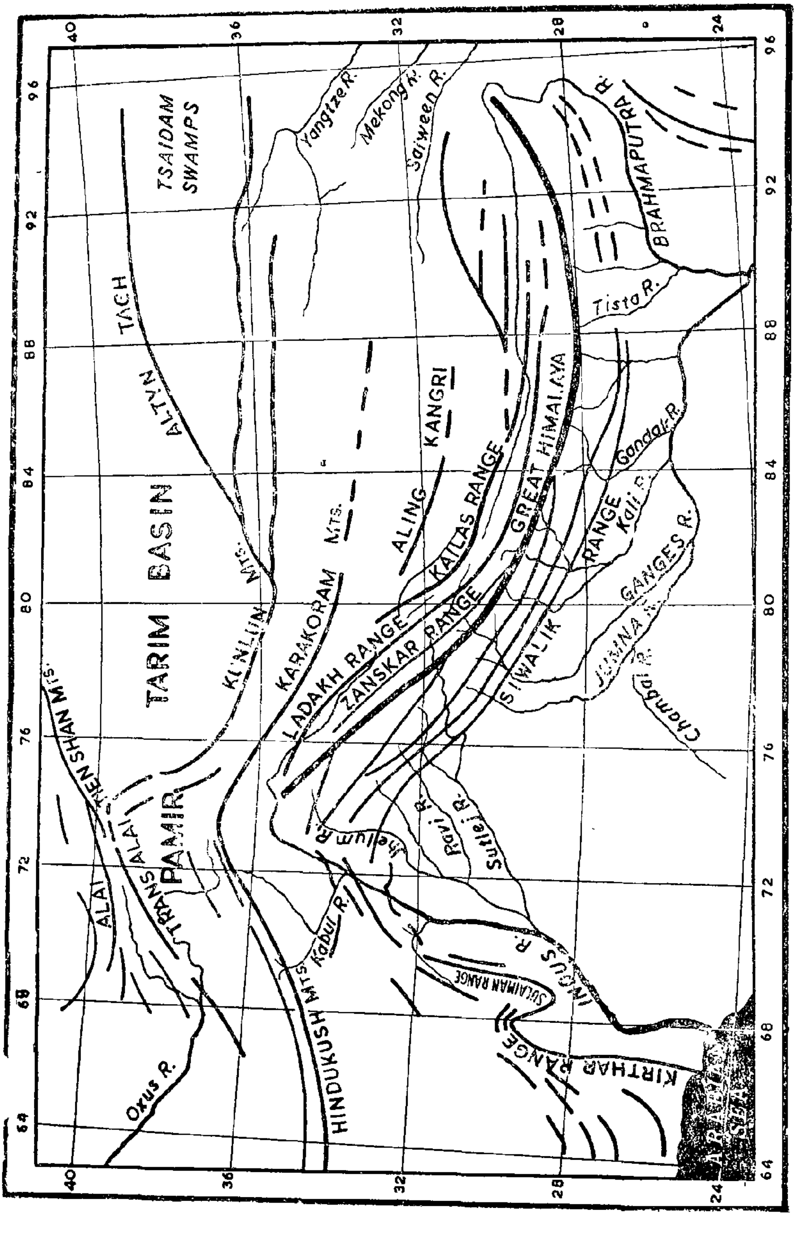
A similar effect is produced by the Punjab-Kashmir wedge in the north-west. The Potwar plateau of western Punjab is a synclinal trough with its axis along an ENE-WSW direction (Fig. 2). The northern border, adjoining the Kala Chitta and Margala hills, is closely folded into steep isoclines and recumbent folds, but the main syncline contains more open folds dipping north with strike faults hading in the same direction. It has probably a sub-stratum of Mesozoic rocks but exposes only Murree (Oligo-Miocene) and Siwalik (Mio-Pleistocene) fromations while along its southern edge Eocene rocks appear. The total thickness of Tertiary sediments aggregating to 25,000 ft., epitomises the Tertiary geology of Punjab and Kashmir (Anderson, 1928 : Wadia, 1932a). The southern border of this plateau is the Punjab Salt Range which presents a conspicuous scarp showing Cambrian sediments followed by a complete succession of marine rocks ranging in age from the Carboniferous to Eocene, and lacustrine and fluviatile sediments of Oligocene to Miocene ages which overlie them and extend northwards over the plateau. The Salt Range shows a faulted flexure in the east which, when followed westwards, is resolved into three parallel overthrusts. The upper limb of this disrupted fold has been thrust over the lower, completely obliterating the latter. The distance over which the rocks have been thrust has been estimated at not less than 20 miles (Gee, 1934a, p. 462). Saline marls associated with gypsum and dolomite appear in all sorts of positions in the overthrust zone and their stratigraphical position has been a source of controversy in Indian geology for many decades.

The presence of a wedge of the Peninsula projecting from North-west Punjab into Kashmir is inferred from the spectacular hair-pin bend of the geological formations in north-western Kashmir, some 75 miles north-west of Poonch. This is the Kashmir-Hazara Syntaxis described by Wadia (1931, 1938). On both sides of the bend, the formations have a NW-SE strike, but the southwestern side soon turns southwards and sweeps in a broad arc convex towards India. Mesozoic and Tertiary sediments as well as the Pre-Cambrian Salkhala formations are affected by this sharp flexure. Around this bend, the overthrust is directed from all sides towards the axial direction (Fig. 5). The effect of the wedge is seen as far north as the Karakoram—Hindu Kush ranges, the Pamir and East Ferghana, as will be seen from the northward bend of all the mountains and of the geological formations north of Kashmir (Hayden, 1915). Mushketov (1929) states that in the Alai Range, which forms the southern border of E. Ferghana in Russian Turkestan, there is an earlier (Tien-shan) folding from the north and a later (Himalayan-Alpine) folding and thrusting from the south which has an imbricate character. It is only in the Red Trough of Alaiku, occupied by red Cretaceous sandstones,



SECTION ACROSS THE POTWAR GEOSYNCLINE

Fig 2. (After D. N. Wadia.)



HIMALAYAS AND CENTRAL ASIAN MOUNTAIN RANGES

Fig. 3.

that the effects of the Tien Shan folding from the north, and of the Himalayan folding from the south, are not noticed.

The effect of two other wedges is seen in the Baluchistan arc. One of these wedges is directed towards Sibi and Quetta and the other northwest from Dera Ismail Khan just south of the Salt Range. In each of these regions the festooning effect of the wedge is conspicuously seen, both in geological and topographical maps.

It would appear that these wedges which are, so to say, underthrust into the mountain belt bordering northern India, are responsible for the high seismicity of the regions lying near their tips (Sadiya, Pamir and Quetta areas) as the disturbance in the sub-crustal part of these regions may be much greater than elsewhere along the belt and will take a longer time to die off and attain equilibrium.

6. The Purana Formations

(Cuddapahs and Vindhyans).

The practically unfossiliferous upper Pre-Cambrians are known as the ' Purana ' formations in India. They comprise the Cuddapahs which are entirely Pre-Cambrian, and the Vindhyans which are probably partly Pre-Cambrian and partly younger and contain discoid fossil impressions assigned to the genus *Fermoria* (Chapman, 1936 ; M. R. Sahni, 1936 ; Misra and Bhatnagar, 1950). They are exposed in the Aravalli fold belt of Rajputana and in three large crescent-shaped areas in Central, Eastern and Southern India. The southern one is the Cuddapah Basin containing Cuddapah and Kurnool (Vindhyan) sediments, which were deposited over the Archaeans after an interval of erosion. The eastern concave margin of this basin, which is parallel partly to the trend of the Dharwarian and partly to that of the Eastern Ghats rocks, is, unlike the western margin, highly disturbed and folded. The older sediments in this basin are the Cuddapahs and the later ones the Kurnools. The Cuddapahs contain intrusive basic sills and have been folded and disturbed to some extent, while the Kurnools are practically unaffected.

The Aravalli belt of Rajputana contains the Delhi System which is considered to be the equivalent of the Cuddapahs, though it has been subjected to intense diastrophism and intruded by granites and other igneous rocks. It is best developed in the synclinorium and extends down to Gujarat, where it pitches downward. It is overlain by the Vindhyan system of rocks which occur mainly in the neighbouring areas.

To the east of the Aravalli belt is the great Vindhyan basin of Northern India, occupying an area of some 40,000 sq. miles. It has also a crescentic

shape, the northern concave margin enclosing the Bundelkhand granite of Archaean age. Its western margin against the Aravalli fold belt is marked by a reversed fault or overthrust, the upthrow on the western side being estimated at 5000 ft. (Oldham, 1893 p. 103) or 3500 ft. (Heron, 1938 p. 128). The Aravallis are brought up against the Bhander Sandstone (Upper Vindhyan) along the fault. This fault, which is parallel to the trend of the Aravallis, and has been traced over a distance of 500 miles or more, is definitely post-Vindhyan and may belong to the Hercynian orogenic period or even to the Mesozoic. Uraninite and monazite from pegmatites intrusive into the Delhis indicated an age of 700 to 865 million years (Holmes, 1949).

The Vindhyans comprise two major divisions, the Lower Vindhyan or Semri Series, and the Upper Vindhyans. The Semri series is seen near the outer borders of the Vindhyan basin in the Son Valley, near Chitor in Rajputana and in the Dhar forest on the edge of the Narbada alluvium east and south-east of Bhopal. The Semris are intruded by basic lavas and show much disturbance and folding. The rocks of the Dhar forest exhibit folding along a NW-SE axis which apparently continues in a northwesterly direction, underneath the Deccan Trap, to Jhalrapatan southeast of Kotah.

The Upper Vindhyans, with which the Kurnools are correlated, consist largely of sandstones and shales deposited in shallow waters and partly under semi-arid conditions as witnessed by the false-bedding of the sandstones, their red colour and the occurrence of gypsum in some of them. They are generally undisturbed except near the southern and southeastern edges of the basin. The movements on the southwestern side have come from southwest whereas in the eastern areas they appear to have come from the south or south-south-east, controlled by the earlier Satpura strike.

The third large area is the group of exposures in Bilaspur, Raipur, Bastar, etc., in the Cetral Provinces which are taken generally to represent the Cuddapahs, and perhaps also the Vindhyans, in part. Here also the more eastern outcrops show some disturbance on the eastern side adjoining the Eastern Ghats. A few other patches of Purana rocks are found along the Godavari Valley and in the Kistna and Bhima Valleys of Southern Bombay and Hyderabad. In these last, the Kaladgi formations (presumed to be the equivalents of the Cuddapahs) are said to be intruded by granite (Iyer, 1939, pp. 518-520).

A fact to which attention should be drawn is that the Delhis, Pakhals Kaladgis and the Puranas of Raipur-Sambalpur area of Orissa and the Central Provinces (V.S. Krishnaswami, 1951) are all intruded by granites. Since the Cuddapahs of Madras, with which these are generally correlated, have not been subjected to granitic intrusion, there are

grounds for reconsideration of such a correlation. As pointed out by Mahadevan (1949), these groups may be really older than the Cuddapahs. The question will have to be kept open until more field and laboratory data on the age of these various groups become available.

It should be stated, however, that while strong mountain building movements affected the Delhi formations, their presumed equivalents in South India experienced comparatively less intense activity. The Lower Vindhyans (Semris) were also subjected to movements of some magnitude, but there is some doubt whether these formations do not really belong to the Cuddapahs. The Upper Vindhyans are everywhere practically unaffected by earth movements except in the Bundi-Karauli region of Rajputana where they are folded to some extent.

There are no formations in Peninsular India younger than the Vindhyans until we reach the period of glaciation in the Middle or Upper Carboniferous. During the whole of this interval, the Peninsula was apparently unaffected by any strong orogenic movements though the Vindhyans must have been uplifted and all land subjected to denudation. If any deposits had been laid down during this interval, they must have been removed completely by erosion.

7. The Gondwana Formations

Gondwana sedimentation was initiated by large icesheets which covered the greater part of the Peninsula and whose motion was responsible for the laying down of the Talchir tillite in Eastern India, the Salt Range and parts of the Himalayas. The direction of ice movement was towards the north in Eastern India and north-west in the Punjab, for we find some characteristic Rajputana rocks amongst the boulders of the Salt Range tillites. In the Himalayan area there are tillites presumed to belong to this age in Kashmir and Hazara (Tanakki and Talhatta boulder-beds), in the Simla-Garhwal region (Blaini and Mandhali boulder-beds), in the Kosi river Valley in Nepal near Barahakshetra (Auden, 1946, p. 346), in the Permo-Carboniferous Lachi Series of North Sikkim (Auden, 1935, p. 155; 1946, p. 346) and at several places in the Sub-Himalayan zone up to east longitude 95°. It is thought that Gondwana glaciation extended to some distance north of Lachi (28°1′ : 88°45′) for the beds in the Lachi Hills must originally have lain further north and brought to their present position by thrusting.

According to Fox, the coal-bearing formations of the Lower Gondwanas were laid down by extensive river systems which flowed from high-lands situated to their south and east. It is therefore likely that the Aravalli-Central India region, the Eastern Ghats and South India constituted high-lands, which might have been depressed to some extent

by the load of ice. The tillites appear to have been deposited in the sea along the northern border of India and in the Salt Range area.

At about the same time, great orogenic disturbances (the Hercynian revolution) were taking place in Asia and Europe, and there is evidence that the Western Altai, Tien-Shan, Kun-Lun, Karakoram, Nan-Shan and Tsin-Lin ranges came into existence. A great mediterranean sea, stretching west to east from Southern Europe through the Balkans, Turkey and Iran to the Himalaya, came into existence. This stretched out further east through what is now the Assam-Burma border and the Arakan mountains. This sea, called the *Tethys* by E. Suess, persisted throughout the Mesozoic but gave place to mountain ranges in the Tertiary. The history of this geosyncline will be dealt with in some detail later. A depression or rift seems to have been formed at about the same time along the valley of the Narbada as far east as Umaria (23°32′ : 80°50′) and perhaps extending further east. The Umaria region was apparently connected through Gujrat and Cutch to the arm of the Tethys stretching into the Salt Range and Baluchistan. The reason for this statement will appear later (see below).

The close of the glacial period is marked by Talchir shales and sandstones containing grains of undecomposed feldspar. This was followed by a cold temperate climate during which the *Glossopteris* flora flourished throughout the southern continents and India. The chief coal-bearing beds in India are the Barakar and Raniganj series, of Lower and Upper Permian age respectively, separated by barren sandstones. The coalfields are situated along three major zones of block faulting (graben), *viz.*, along the Damodar-Son, Mahanadi and Godavari valleys. In the Damodar-Son Valley the southern sides of the blocks are more deeply faulted than the northern; in the Godavari and Mahanadi basins the north-eastern sides are faulted down more than the south-western. The faulting may, to some extent, have taken place *pari passu* with the sedimentation.

In the Umaria basin mentioned above, a small outcrop of marine Lower Permian rocks was found a few years ago, overlying the Talchir tillite and underlying the Barakars. This zone is rich in Productids and a few other genera of brachiopods and some small gastropods; these have some similarity to the Salt Range fauna and are assigned to the Permo-Carboniferous, *i.e.* equivalent to the Speckled Sandstone group and the *Eurydesma* and *Conularia* beds of the Salt Range (Reed, 1928). Since it is only in Kathiawar and Cutch that there are marine strata younger than these beds, and since it is known that the Narbada valley is a zone of weakness, it appears most probable that the Salt Range sea was connected with Umaria through these regions (Krishnan, 1949, p. 284).

In the Salt Range area, the Talchir tillite is immediately overlain by shales containing impressions of *Gangamopteris*, *Glossopteris* and spores probably belonging to these and allied plants (Virkki, 1937, 1939). Many of these spores were found to be almost identical with those of the Bacchus Marsh beds of S.E. Australia (B. Sahni, 1939). These tillites are overlain by the Olive series containing *Eurydesma* and *Conularia*-bearing horizons. The Olive series is overlain by the Productus Limestone group of Permian age.

In Kashmir, the Hercynian revolution produced land conditions in some parts and the Panjal volcanic episode commenced. The Agglomeratic Slates of Upper Carboniferous age contain intercalations of marine strata with Productids, Spiriferids, *Fenestella*, etc., and also plant beds with *Gangamopteris*, *Glossopteris*, etc., and the amphibian *Archegosaurus*. An *Eurydesma*-bearing horizon is found just below the *Gangamopteris* beds. The plant beds are overlain by the Zewan beds containing marine Permian fossils similar to those of the Salt Range and the Spiti valley.

The volcanic episode and partial land conditions in Kashmir continued throughout the Permian and well into the Triassic, so that intermigration of plants between this area and Angaraland and Cathaysia was possible through the Pamir and Ferghana region. East Ferghana was characterised by continental conditions from the Upper Carboniferous to the Jurassic and a marine transgression took place only in the Cenomanian, according to Mushketov (in Gregory, 1929). The Hercynian revolution produced land conditions also in Northern Afghanistan and Eastern Iran, which lasted through the Permian and Triassic.

In the Spiti Valley, north of the main Himalayan range, there was a *Rhacopteris* flora in the lower part of the Middle Carboniferous Po Series, whose upper part is marine. After the Hercynian revolution, the Tethys Sea was established in the Himalayan area.

Gondwana strata, often coal-bearing, are found in the Giridih and Rajmahal regions north and north-east of the Raniganj field of Bengal, where they have been faulted down along radiating fractures; along the western edge of the Garo Hills of the Assam plateau (Sale and Evans, 1940, p. 344); and at several places along the Sub-Himalayan zone eastward from Nepal up to about E. longitude 95° in the Abor Hills, where they are found generally crushed by the mountain building movements and overthrust by older rocks. It is therefore clear that the Lower Gondwana fluviatile and lacustrine sediments were laid down along the Sub-Himalayan region which formed the northern edge of the Peninsula.

The humid conditions which permitted the growth of luxuriant vegetation in the Permian gave place to dry continental conditions

in the Triassic. The sediments of this period are red sandstones and sandy clays (Panchet and Mahadeva Series) probably laid down in lakes. They have yielded remains of some amphibians and reptiles. The *Glossopteris* flora dwindled and gradually gave place to the *Thinnfeldia-Ptilophyllum* flora. The latter attained prominence in the Jurassic, when moist conditions returned again and the Rajmahal, Kota and Jabalpur beds were laid down. The differentiation which existed amongst the four distinct floras of the Permian (*viz.*, the Arcto-Carboniferous flora of Europe, the Angara flora of Siberia, the Cathaysian or *Gigantopteris* flora of China and the Gondwana or *Glossopteris* flora of Gondwanaland), had disappeared and the Jurassic flora became uniform all over the globe.

The Upper Gondwanas are well developed in the Rajmahal area at the head of the Ganges delta, in the Janakpur-Sohagpur area of the Son Valley, in the Jubbulpore and Pachmarhi regions in the Central Provinces, in the Godavari Valley, Gujarat, Cutch, Jaisalmer in Rajputana and a few places along the east coast. In the last, plant beds referable to the Jabalpur or Kota stages (Middle or Upper Jurassic) are associated with marine beds. Some ammonites in the marine beds, not too well preserved, have been assigned a Neocomian age by Spath (1933) from their evolutionary characteristics. The East Coast Gondwanas may therefore be of Middle Jurassic to early Cretaceous age, and indeed, Cotter (1938, p. 36) was of the opinion that the Upper Gondwanas of the East Coast were of Lower Cretaceous age. In the Rajmahal Hills, plant-bearing beds occur intercalated with thick lava flows. These are thought to belong to the Middle Jurassic. The Sylhet Traps of the Assam plateau and the lavas in the Abor Hills of the eastern end of the Himalayas, as well as the dykes of lamprophyre, peridotite and basalt which traverse the eastern coalfields, are all regarded as of the same age.

The chief phase of block-faulting which affected the Gondwana strata in India may be of Upper Triassic to Lower Jurassic age. In the Damodar valley coalfields, most of the dykes (presumed to be of Rajmahal, *i.e.* Middle Jurassic, age) are later than the faults traversing them. In the Karanpura coalfields some faults are pre-Mahadeva (pre-Upper Triassic). The boundary faults of the Damodar Valley coalfields run practically E-W, more or less *en echelon*, but in the Son valley area they run ENE-WSW, parallel to the Satpura trend and the Narbada rift. There is a series of fractures associated with block-faulting, radiating to west, north-west and north from the Raniganj area in W. Bengal, and in these are situated the several small coalfields of southeastern Bihar including the Giridih and Rajmahal fields. These may have been contemporaneous with the fissures through which the Rajmahal Trap was erupted. Whether other fractures were formed trending

north-east from the same focus towards Bhutan, is a matter of speculation, as that direction is entirely covered by the Gangetic alluvium. If such fractures did exist, they would have been the fore-runner of the Garo-Rajmahal gap about which there has been much discussion recently (Hora *et. al.*, 1949).

After this period, and probably in the Middle Cretaceous, the Gondwanas underwent folding movements which affected the strata in the Son valley more than those in the Damodar valley, though the latter also have been affected to some extent. The age of this movement was post-Jabalpur, for there is a large unconformity between the Jabalpurs (Upper Jurassic) and the Lametas (Upper Cretaceous). We often find horizontal traps resting on the folded Gondwanas with a marked disconformity. The base of the Gondwanas is found at different elevations in different places (Auden, 1949 a, p. 320)—200 ft in Bengal and 3,000 ft. in Sohagpur and Chhindwara in the Central Provinces. Where depressed by block-faulting or folding, the base is several hundreds or thousands of feet below sea-level, *e.g.*, 400 ft. or more in the chief troughs. The age of the folding was probably the same as that which affected the Jurassic rocks of Cutch in Middle Cretaceous times (post-Aptian and pre-Maestrichtian) which will be adverted to later.

We may now turn to the Extra-Peninsular region comprising the Himalayan, Burmese and Baluchistan arcs and consider the sequence of events there as well as along the coasts of India.

THE EXTRA-PENINSULAR REGION

1. The Himalayan Arc

The Himalayan arc lying to the north of India is one of immense radius and extends from Nanga Parbat (26,620 ft.) on the west to Namcha Barwa (25,445 ft.) on the east. The term 'Himalayan Arc' is used here in an orographic and geographical sense to designate the unit comprising the Himalayan mountain chains for, geologically and structurally, it continues into the Baluchistan and Burma arcs at either end, as will be made clear later (Wadia, 1931 ; 1932 ; 1936). It consists of a series of more or less parallel ranges which are succeeded further north by still more ranges. But in that direction the curvature of the successive ranges gradually lessens.

The Himalayas are generally divided into four longitudinal zones. The outermost, bordering the north Indian plains, consists largely of the Siwalik formations (Mio-Pleistocene), forming low hills and of varying width, up to 30 miles wide. The next is the Sub-Himalayan zone (also called Lesser Himalayas), about 50 miles in width and on an average 7,000—10,000 ft. in altitude though some points are much higher. It contains sediments of various ages from the Pre-Cambrian upwards, most of them generally unfossiliferous. Amongst them are the Talchir tillites at the base of the Gondwanas as well as coal-bearing Lower Gondwanas at many places. This contains several overthrusts and nappes in which recumbent folds and inverted sequences are common. This represents the border of the former land mass of India and the marine basin which lay immediately beyond. Beyond this comes the Central Himalayan zone, some 40 miles wide, containing practically all the snow-clad high peaks. It consists of some sedimentary and metamorphic rocks and large masses of igneous intrusives. The Central Himalayan granite is probably of different ages, largely Kainozoic and possibly partly Mesozoic. Beyond this is the Himalayan Tethyan zone composed of sediments of all ages formed in the Tethyan geosyncline. It contains the valleys of the Indus and the Brahmaputra draining the northern ranges of the Himalayas, the altitude of the river basins being about 12,000 to 14,000 ft.

Between the Tethyan zone and the Karakorum Mountains is the little known region of Tibet, containing the Aling Kangri and the Trans-Himalaya ranges of Seven Hedin, the latter being the real watershed between India and Tibet. The Karakorum range is roughly parallel to the Himalayas but is bent northwards in the Pamir region beyond which its western continuation is called the Hindu Kush. Still further north is the Kun Lun range which has

also been affected by the Alpine-Himalayan orogeny. The Pamir region is a mountain knot showing the remarkable feature of radiating mountain chains.

MOUNTAIN ARCS OF SOUTHERN ASIA

We shall now proceed to give a short description of the structure of the Himalayas as deciphered in the few areas in which they have been examined in some detail in recent years.

Commencing with Kashmir, at least three major thrust zones are recognised in the Siwalik and Lesser Himalayan region. The southernmost is the *Main Boundary Fault* which usually separates the Siawliks from the earlier Tertiaries and older rocks. To the north of the Tertiary belt is the autochthonous (more correctly para-autochthonous) zone

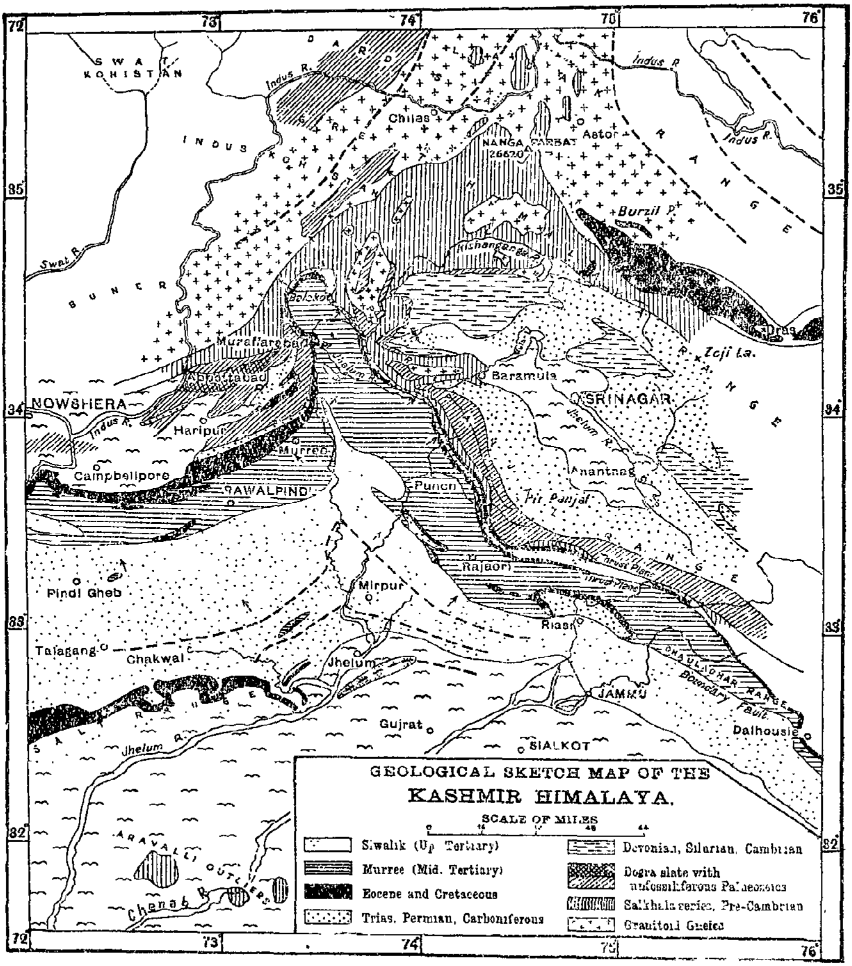
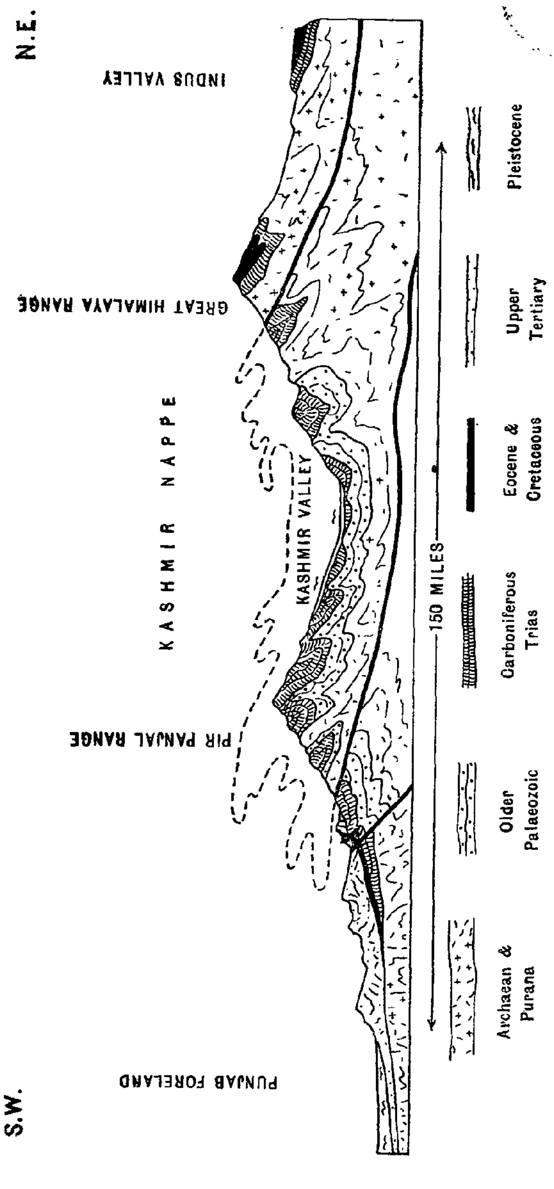


Fig. 5. (After D. N. Wadia.)

containing sediments of all ages from the Carboniferous to the Eocene. These are folded and thrust over the rocks of the foreland. This thrust is called the *Murree thrust.* Beyond this is the zone of nappes (Kashmir nappes) in which at least two important thrusts are known to be present.



SECTION ACROSS THE KASHMIR HIMALAYA TO SHOW THE BROAD TECTONIC FEATURES
(After D. N. Wadia)

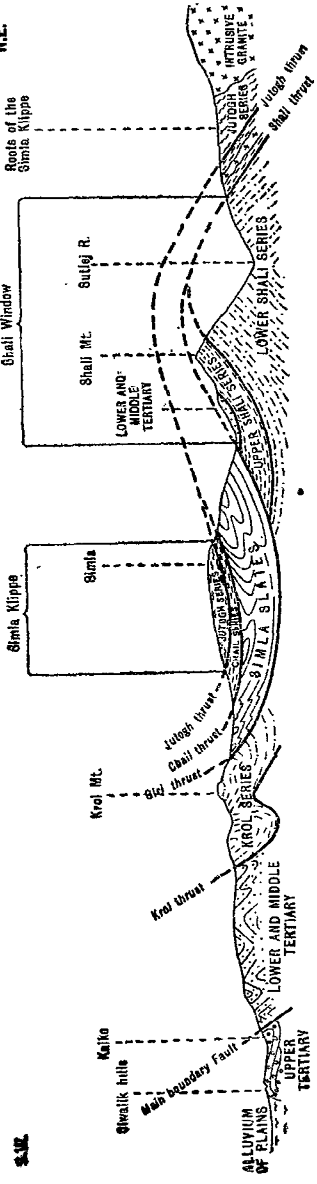
Fig. 6.

The Pre-Cambrian, Palaeozoic and Mesozoic rocks of the nappe zone are thrust over those of the autochthonous zone. These constitute the *Panjal thrusts.* Further to the north is the Central or Main Himalayan Range intruded by granites of presumably Cretaceous and Tertiary ages (Wadia, 1934 ; 1938). Fig. 5 shows the geology of the Kashmir region while Fig. 6 shows a hypothetical section across Kashmir.

In the Simla region, which has been mapped by Pilgrim and West (1928 ; West 1934) and by Auden (1934), the *Main Boundary Fault** separates the Middle and Upper Tertiaries from the Lower Tertiaries which have been thrust over them. The Upper Tertiaries, which have a width of over 60 miles in Kangra, become narrowed down to barely 16 miles near Solon, south of Simla. The Tertiaries are separated from the pre-Tertiary rocks of the autochthonous belt by the *Krol thrust* which thus corresponds to the Murree thrust of Kashmir. Beyond this is the zone of nappes with the *Jutogh* and *Giri thrusts.* Further north is the important *Chail thrust* with its Pre-Cambrian and Palaeozoic rocks, under which the Shali window described by West (1939) exposes the Shali limestones, slates and quartzites (Mesozoic), as well as Madhan slates (Tertiary). Nummulitics and Dagshai beds (Miocene) have also been found in the above-mentioned window. Granitic intrusives are found in the nappe zone and along the Main Himalayan range. The nappe zone shows several klippen of highly metamorphosed ancient rocks resting on less metamorphosed unfossiliferous Palaeozoic and later rocks (Fig. 7).

To the E.S.E. of Simla is Garhwal where the *Main Boundary Fault* separates, as usual, the Siwaliks from the autochthonous zone of Simla States (Palaeozoic) overlain by Nummulitics and other Lower Tertiaries. This zone is over-ridden by the Krol nappe (Krol thrust) which contains rocks of various ages from the Pre-Cambrian to the Mesozoic (Fig. 8 and Pl. 1). The Giri thrust unit lies over the Krol thrust unit of the Simla area which is known to extend to the east beyond Naini Tal. Further north are the Garhwal nappes which bring highly metamorphosed Pre-Cambrians and some Palaeozoics over the Krol belt (Auden, 1934). The Garhwal nappes, with their roots in the Main Himalayan range, have also transported the granites with them. Both the Krol and the Garhwal nappes are folded, which Auden believes (1937, p. 429) may be due to the resistance offered by the floor over which they moved southwards. Since the Krol thrust overlies the Dagshai beds, it cannot

*There is some confusion in the use of the term *Main Boundary Fault.* It was originally used by H. B. Medlicott who suggested that it marked the boundaries of deposition of the Nummulitics from the post-Nummulitic rocks, or the Tertiaries from the pre-Tertiaries (Medlicott, 1865, *Mem. Geol. Surv. India,* III, Pt. 3, 81-84, 174). This idea is erroneous. The Main Boundary Fault is known to be a thrust zone which generally separates the post-Nummulitic Tertiaries from the pre-Nummulitics (West, 1937, *Proc. Ind. Sci. Cong.* p. 205 ; Auden, 1938, *Proc. Ind. Sci. Cong.* Pt. IV, p. 20.)



SECTION THROUGH THE SIMLA HIMALAYA.

Fig. 7

(After W. D. West.)

be older than the Burdigalian. The Garhwal thrusts cover the Nummulitics and may therefore be also of Miocene age (Auden, 1934). Several tectonic windows have been found in recent years in the Lesser Himalayan belt (Auden, 1937 ; 1951, figs. 4, 6).

Nepal and the Eastern Himalayas have not been examined in detail, but enough is known to enable us to say that the structure is similar to that of Garhwal and Kashmir. In Nepal, a thrust separates the Middle and Upper Siwaliks from the Lower. The Tertiaries are overridden by pre-Tertiary rocks (para-schists, Palaeozoics and Krol series)

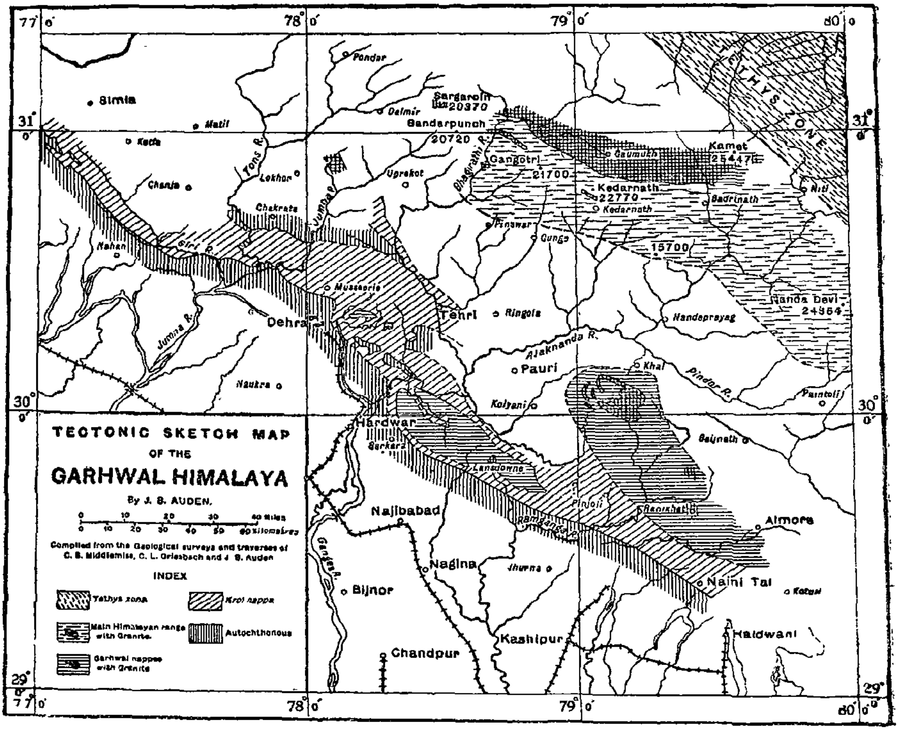


Fig. 8. (After J. B. Auden.)

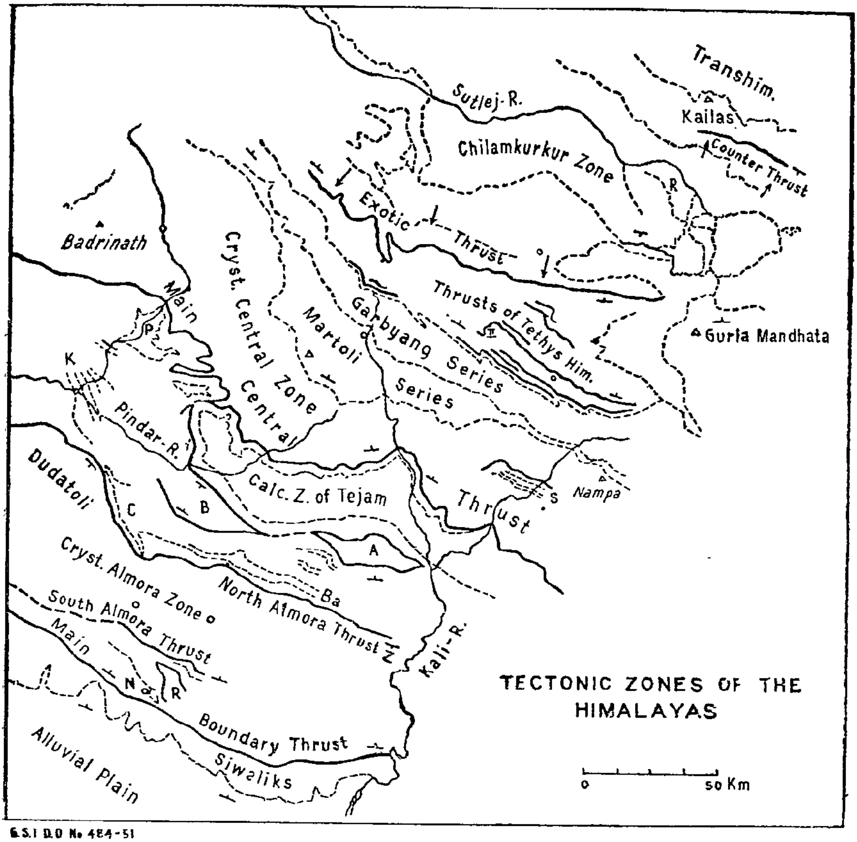
by another thrust, seen near Sanotar. A third thrust brings the Pre-Cambrian Darjeeling gneiss and Daling schists over the above-mentioned zone (Auden, 1935, pp. 136-147).

Information on Sikkim is scattered, but here also the Main Boundary Fault and one or more other thrusts have been recognised. Coal-bearing Gondwanas are thrust over the Siwaliks in the Darjeeling foot-hills, the Gondwanas being in turn overlain by older rocks. Permian and Mesozoic sediments are exposed in Northern Sikkim and in the Mt. Everest

region where a glacial boulder bed is associated with the Permian Lachi series (Wager in Ruttledge, 1934, p. 333 ; Auden, 1935, pp. 147, 154).

In their important work on the Geology of the Himalayas, Heim and Gansser (1939) have reviewed the tectonics of the entire Himalayan belt from the plains of India to the Trans-Himalayna Range (Fig. 9).

The Siwalik zone bordering on the Gangetic plains is thrust over



G.S.I D.O No. 484-51

Fig. 9. (After A. Heim and A. Gansser.)

by the Miocene rocks in the Kalka region below Simla. The Karewa formations in Kashmir, of Middle Pleistocene age, are known to have been uplifted a few thousand feet on the flanks of the Pir Panjal range. The Second Inter-glacial deposits which contain the remains of early tool-making man have suffered uplift in North-western Himalayas, according to de Terra (1937 ; also B. Sahni, 1936, pp. 10-16). In parts

of the Eastern Himalaya, especially in the Darjeeling and Bhutan regions, the thrust masses have advanced on to the plains, the age of the thrust being later than the Upper Siwalik Conglomerate (*i.e.*, Pleistocene).

The Lesser Himalayas of Garhwal show *at least four superimposed thrust sheets* lying over the Nummulitics and other rocks associated with them. According to these authors (1939, p. 219) the thrust synclinal of Naini Tal is the continuation of the Krol belt. This is thrust over by the gneisses, schists, etc. of the Ramgarh region and this again by the crystalline zone of Almora. The northern-most zone of the Lesser Himalaya is the calcareous zone of Tejam which may possibly represent the Krol-Tal succession though the rocks are much more metamorphosed than the typical Krol-Tal rocks.

After this appears the great crystalline zone of the Central Himalayas containing schists and ortho-gneisses invaded by huge masses of granite. These are thrust on top of the Tejam zone.

Beyond this comes the Tethyan belt containing repeated thrusts Heim and Gansser have called the first of these the *Nihal thrust*. The second is the *Thumka Gad thrust* seen near Kuti which shows tight folds of Kioto limestone (Rhaetic), in the synclinal portions of which there appear the Spiti Shales (Jurassic). A third thrust appears near the Manshang Pass where the Silurian is repeatedly brought up against and over the Permo-Triassic rocks. All these are thrust over by the Cretaceous flysch associated with the exotic limestone blocks of Permian to Cretaceous ages and basic igneous intrustives and lava flows, from the north-east. These exotics and associated rocks do not belong to the Himalayan Tethyan belt but must have come from Tibet. The exotic blocks belong to a facies similar to the European Triassic Dachsteinkalk, Jurassic oolites, Cretaceous limestones, shales, crinoidal limestone and radiolarian cherts. The exotic blocks and associated rocks are repeated in the Shib Chu valley and also in the Amlang La and Jangbwa areas west of Raksas Tal.

Beyond this is the sedimentary zone of the Chilamkurkur and Raksas series which are dominantly shaly and of Mesozoic age. Still further north is the Darchen zone of flysch with associated igneous rocks and limestone blocks which might possibly represent the root zone of the Kumaon exotics mentioned above. But the Darchen rocks are thrust in a north-easterly direction—regarded by Heim and Gansser as a counter-thrust—over the Eocene conglomerate zone of Mount Kailas which here occupies a wide zone. Beyond Mount Kailas is the Trans-Himalaya Range with its granites and metamorphics

Summarising, we may say that the following thrust zones have been established from south to north :—

1. Imbricate thrusts of the Himalayan border and the Simla region.
2. Thrusts of the interior Lesser Himalayas.
3. Thrusts of the Crystalline Central Himalayan zone in which Mt. Everest and Kanchanjunga are included.
4. Repeated thrusts of the Himalayan Tethyan zone.
5. Thrusts of the Exotic block—flysch zone of Tibetan facies.
6. The counter-thrust Darchen zone which may be the root of No. 5.

The exotic block zones contain ultrabasic rocks including peridotites and serpentines, while the Central Himalaya and Trans-Himalaya contain large granite intrusions. These should represent the central and most highly disturbed belt of geosynclinal sedimentation which was subsequently lifted up into great mountain ranges.

Geographically, the Himalayas terminate at Namcha Barwa in the east. Some think that the eastern continuation of the Himalayas are to be looked for in the mountain ranges of South-Western China. Though that region is still little known, all the available knowledge goes to show that, geologically, the Himalayan formations turn sharply southward and form the Burma-Arakan ranges which will be referred to here as the Burmese Arc (Wadia, 1936). The north-easterly strike of the eastern end of the Himalayas turns sharply to a S.E. direction beyond the Sadiya frontier region, then S.W. and finally South. The Shan region of Burma is geologically a part of the Yunnan-Indochina Province, and its proximity to India was brought about only in post-Cretaceous times. Moreover, the drainage and ridge-pattern of the Assam-Tibet-Burma—S.-W. China region shows a radiating arrangement somewhat like that of the Pamir, as pointed out on a previous page.

2. The Burmese Arc.

This arc commences just beyond the north-east corner of Assam and sweeps in a broad curve through Arakan and Andaman islands into Sumatra and beyond (Fig. 10). It is convex towards India but there is a slight concavity in the Arakan region, probably due to the existence of a part of the Peninsular shield under the Ganges-Brahmaputra delta. The southern part of the Burmese arc is largely submerged in the Bay of Bengal, the Andamans and Nicobars being the unsubmerged peaks of its ridges. Our knowledge of the geology of the Assam-Burma border is sketchy, but it is known that the mountain ranges here are composed of folded Mesozoic and Tertiary rocks, intruded by granitic and ultrabasic rocks. In the core of this belt are Triassic and Cretaceous

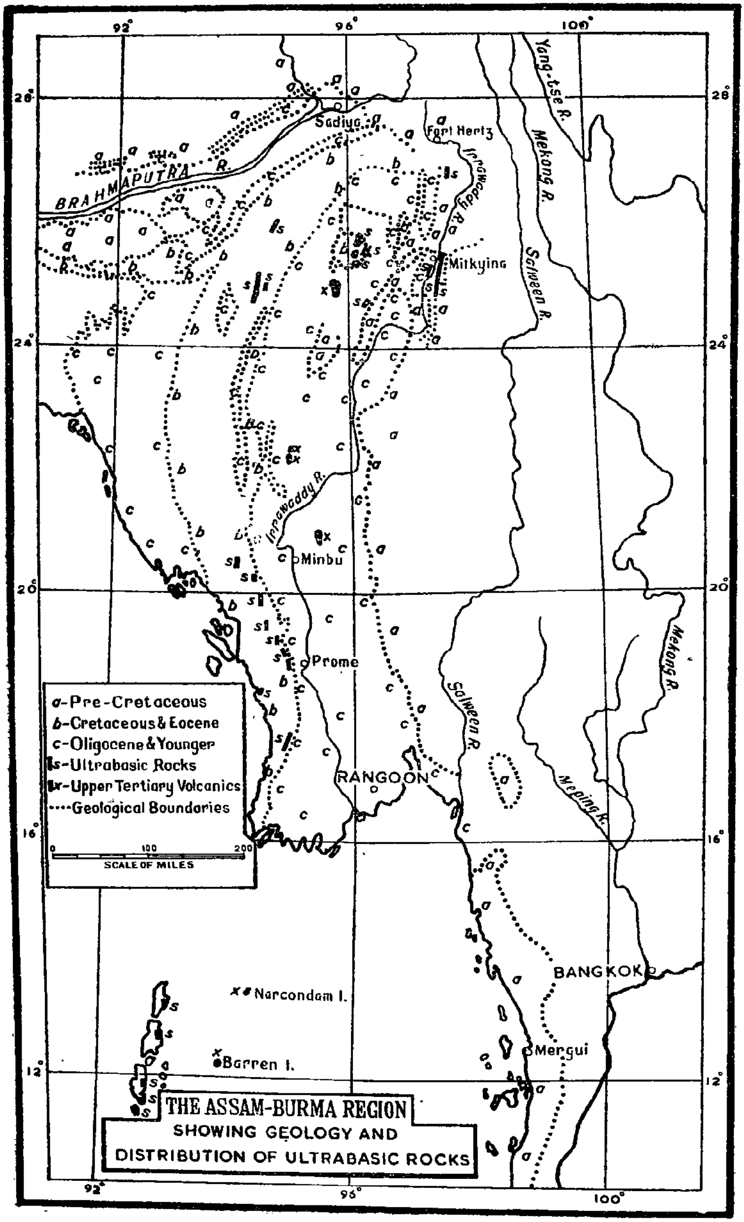

THE ASSAM-BURMA REGION
SHOWING GEOLOGY AND
DISTRIBUTION OF ULTRABASIC ROCKS
a-Pre-Cretaceous
b-Cretaceous & Eocene
c-Oligocene & Younger
s-Ultrabasic Rocks
x-Upper Tertiary Volcanics
····Geological Boundaries
0 100 200
SCALE OF MILES
92°
96°
100°
28°
24°
20°
16°
12°
BRAHMAPUTRA R.
Sadiya
Fort Hertz
Irrawaddy R.
Yang-tse R.
Mekong R.
Salween R.
Mitkyina
Minbu
Prome
RANGOON
Meping R.
BANGKOK
Mergui
Narcondam I.
Barren I.

Fig. 10.

rocks which were folded in the Upper Cretaceous and also subsequently in the Tertiary.

Two important overthrusts—the Naga and the Haflong-Disang thrusts—and several smaller thrusts and reversed faults are known on the Assam side of this arc. In all cases the thrust is directed from Burma towards India in a N.-W. or westerly direction.

Inside this arc, and parallel to it, is the main volcanic zone with Upper Tertiary to Recent Volcanoes—of the Jade mines area, Prome, Tharrawaddy, Barren Island, Narcondam—continuing into the volcanic zone of Sumatra, Java and other islands of the Indonesian archipelago. This zone lies at the faulted junction of the eastern border of the main Burma-Arakan range and the western border of the median Tertiary belt of Burma. Most of the volcanoes in this zone were active in Upper Miocene to Pleistocene times. (Chhibber, 1934, p. 284).

The next is the median Tertiary belt of Burma which contains the oil fields. The Tertiary gulf which occupied this area was gradually filled up by sediments which are of fresh to brackish water character in the north and marine in the south. There are stratigraphical breaks in Upper Eocene and Upper Miocene and a palaeontological break in Upper Oligocene. The Tertiary rocks are faulted against the more ancient rocks of the Shan plateau belt which lie to their east. In this fault zone is another line of volcanic rocks—the basic and intermediate lavas of Kabwet and Mandalay and the rhyolites of Thaton.

The Shan belt shows Pre-Cambrian, Palaeozoic and some Mesozoic rocks intruded into by Pre-Cambrian and Mesozoic (presumably Jurassic) granites. This granite belt passes through Bhamo and Mogok in the north and through Tenasserim into the Malay States in the south. The Shan belt is geologically allied to S.W. China and Indo-China.

3. The Baluchistan Arc

The Geological formations in Kashmir which have a general northwesterly trend, bend round sharply in the region southwest of Nanga Parbat. This deflection is particularly well seen northwest of Poonch, on the Kashmir-Hazara border (Wadia, 1931). It spreads out further south, a part going through Hazara into Safed Koh Mountains and Afghanistan and the other into the Sulaiman and Kirthar ranges of the Sind-Baluchistan border and into Mekran and Eastern and Southern Iran (Fig. 11). In contrast with the smooth-flowing broad curve of the Burmese arc, this shows three conspicuous festoons, because of the "gathering up" of the strata in the Dehra-Ismail Khan and Quetta regions The overthrust in this arc is from the northwest and west, and *towards India* as in the other cases. The festoons are evidently to be attributed

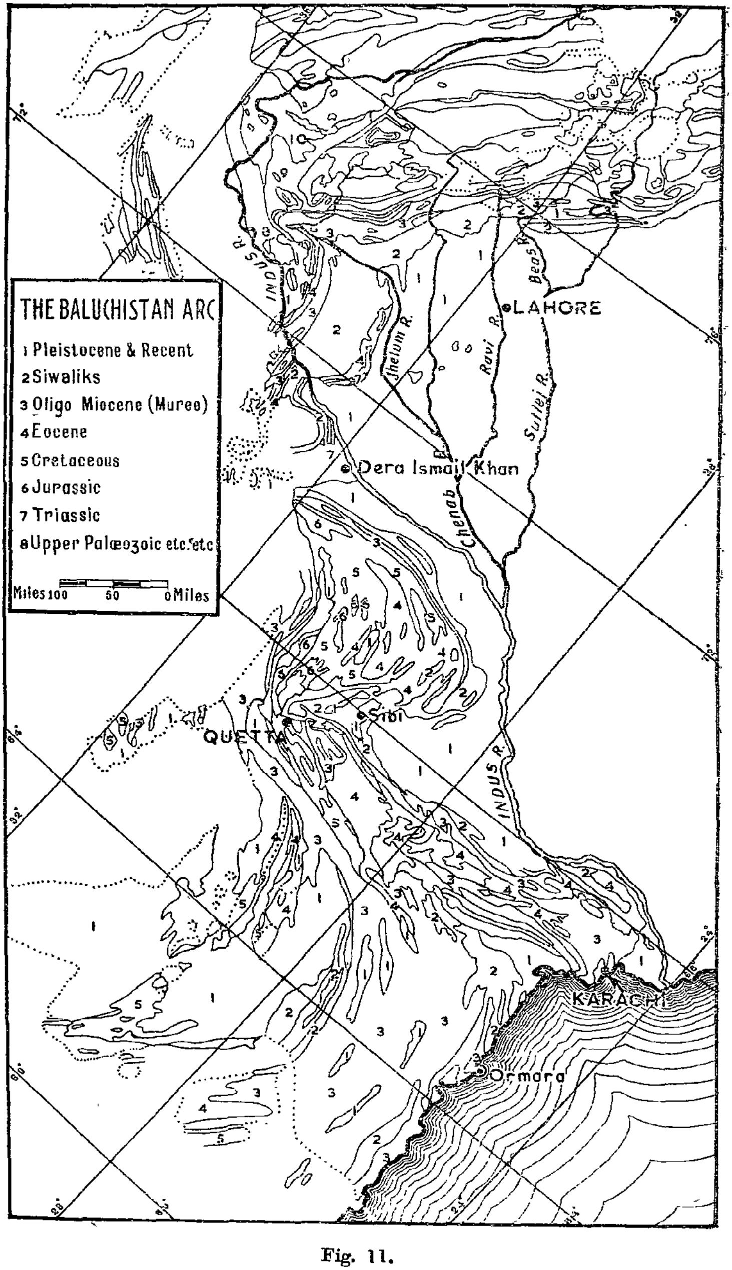

THE BALUCHISTAN ARC
1 Pleistocene & Recent
2 Siwaliks
3 Oligo Miocene (Muree)
4 Eocene
5 Cretaceous
6 Jurassic
7 Triassic
8 Upper Palæozoic etc.etc
Miles 100 50 0 Miles
LAHORE
Dera Ismail Khan
QUETTA
Sibi
KARACHI
Ormara
INDUS R.
Jhelum R.
Ravi R.
Beas R.
Sutlej R.
Chenab

Fig. 11.

to the presence of wedges of ancient rocks, underlying the Indus alluvium, in the Dehra-Ismail Khan and Sibi-Quetta regions. On the convex side of the arcs lie the Murree (Oligo-Miocene) and Siwalik (Mio-Pleistocene) sediments, while on the cancave side lie Mesozoic sediments as well as Tertiaries of the *flysch* type.

In the north, in Hazara, two sedimentary facies lie side by side having a general south-west trend. The northwestern facies is of the Himalayan or Spiti type while the south-eastern (referred to frequently as the Calcareous zone) is a calcareous facies which continues into Sind-Baluchistan. The Calcareous zone in Sind-Baluchistan exposes Permo-Carboniferous, Upper Triassic, Jurassic, Cretaceous and Eocene rocks striking into the sea near Karachi, but soon after turning southwest towards Oman in Arabia. In this zone there are basic and ultrabasic intrusives as is the case in the Burmese arc.

South of Quetta and west of the Kirthar range, the formations spread out and turn westwards, going into Southern Iran. The Tertiary rocks here contain intermediate and basic volcanics as well as some volcanic cones which were active in the Upper Tertiary (one still active). This region seems to have been more highly folded and faulted than the corresponding Tertiary belt of Burma. The productive oil fields of Burma have survived apparently because that region has suffered less disturbance than Baluchistan.

4. Pre-Cambrian

The Pre-Cambrians of the Himalayas belong entirely to what was originally the northern border of India. They consist of an earlier group of gneisses and schists and a later group of metamorphosed sediments corresponding to the Delhis and Cuddapahs. In Kashmir they are called Salkhala series, Dogra Slates and Attock Slates ; in the Simla-Garhwal region, the Jutogh and Chail series and Simla Slates ; in the Darjeeling region, the Darjeeling and Daling series ; in Bhutan, the Buxa series, etc. In the Darjeeling area, they abut against the plains without the intervention of a zone of Siwaliks which may be due to their being thrust further south over all the younger rocks during one of the late Tertiary movements (Heim, 1938 ; Heim and Gansser, 1939, pp. 5-6 ; Auden, 1949*a*, p. 330). The Himalayas to the south of the main range are to be regarded as part of the Peninsula, though their relationships are difficult to decipher because of the intense folding and overthrusting they have undergone.

Beyond the Central Himalayas, the Archaean and Pre-Cambrian are represented by the Vaikrita system (Griesbach, 1891, p. 41) consisting of schists, gneisses, limestones, quartzites, etc. and by the Martoli

Series (Heim and Gansser, 1939, p. 202) consisting mainly of quarzites and phyllites deposited as clays, sands and marl in a sinking geosynclinal basin and considered as of Algonkian age. The Martoli series represents part of the Haimanta system of Griesbach, and constitutes the well known peaks of Nanda Devi and Nanda Kot.

Archaean and Pre-Cambrian rocks in Burma are found in the Shan-Tenasserim belt, extending into S.W. China. It is not known whether the Archaeans in the Sadiya tract of Assam are continuous with those of Upper Burma or separated from them by a zone of sediments.

5. Cambrian

Cambrian strata are well developed in the Punjab Salt Range where they consist of purple ferruginous sandstones, shales and dolomitic sandstones. Saline marls with beds of salt and gypsum as well as some basic igneous rocks are associated with them. The fossils found include *Redlichia, Anomocare, Ptychoparia,* etc. The Cambrian development in the Baramula area of Kashmir and in the Spiti area of the Himalayas has also identical or closely related fossils.

In Spiti and Kumaon, Heim and Gansser (1939, pp. 202-203) state that the basal Cambrian is formed of the Ralam series (conglomerates, quartzites and massive yellow dolomite) followed by the Cambrian Garbyang series (slaty phyllites, dolomite and calcareous sandstones and shales containing trilobites and crinoids). The Garbyang series is equivalent to part of Griesbach's Haimanta system as shown by Hayden (1904).

Similar marine fauna with *Redlichia* and *Anomocare* is found in north-central and eastern Iran (Clapp, 1940). The Hormuz Series of the Persian Gulf region shows a great deal of resemblance to the Salt Range both in lithology and fossils. (de Bockh, Lees and Richardson—in Gregory, 1929).

No Cambrian strata have been found in Burma, but rocks of this age with *Redlichia* fauna is known in S.W. China (Eastern Yunnan, Szechuan and the Yangtse gorge). Upper Cambrian rocks are absent from here, but the sea transgressed again in the uppermost Cambrian, bringing in a fauna related to that of the Baltic region (Lee, 1939).

According to Du Toit (1937, p. 126), the *Redlichia* fauna of the Cambrian characterises a lengthy trough extending from Iran through the Himalaya into the Kimberley region of N.-W. Australia, South Australia and Tasmania, with an arm extending into Yunnan and Tonkin. This fauna had affinities to the North American fauna of the same age.

6. Ordovician and Silurian

These two systems are well developed in Kashmir and Spiti, but not in the Salt Range where the Cambrian is overlain by the Talchir tillite. In the Himalayan Spiti area there is a thick succession of sandstones, shales and limestones of Ordovician and Lower Silurian ages, while the Upper Silurian forms part of the Muth Quartzite which is mainly of Devonian age. In the region of the Shiala Pass and the Dhauli valley there are calcareous sandstones, red crinoidal limestones and the 'Variegated series' (limestones, shales of varied colours) of these ages. The Variegated series occurs in the Zanskar range beyond Kumaon. The Himalayan fauna is rich in corals and brachiopods but devoid of graptolites. Rocks of these ages occur also in S.-W. Iran. In the Shan States of Burma, the Ordovician and Silurian are characterised by abundant graptolites, but few corals.

Ordovician strata containing graptolites and *Orthoceras* are found in Yunnan and S.W. China where there is a break in the Upper Ordovician and folding took place in Upper Silurian. The Burma and S.W. China fauna is closely allied to that of the Baltic region, while the Himalayan fauna shows affinities to that of N. America.

The Lower Palaeozoic is not represented in Malaya and the Indonesian archipelago. In Australia, the Cambrian sea moved eastward and the Ordovician and Silurian fauna is similar to that of S.-W. China and the Baltic. Orogenic disturbances took place at the end of the Ordovician and in Upper Silurian (David, 1950, pp. 168, 213).

7. Devonian

The characteristic formation of this period is the Muth Quartzite in the Western Himalayas in Spiti and Kashmir, where it consists of massive quartzite with intercalations of limestone, the quartzite being generally unfossiliferous. Limestones with brachiopods and corals are found along a more northerly zone in parts of Nepal, Spiti, Chitral, Afghanistan and Turkestan. In eastern and northern Iran, the Lower Devonian consists of red sandstones with gypsum while the Upper Devonian is marine, resembling the limestone facies of the Himalayan region.

In the Shan States of Burma, the Devonian is represented by the lower part of the 'Plateau Limestone'. Fossils have been found in two areas, one being a marine facies (Padaukpin limestone) with brachiopods and corals, and the other lagoonal (Wetwin Shales) with mollusca. The Devonian is also well developed in South China. The Middle Devonian (Eifelian) was a period of extensive marine transgression here and in Indo-China, and is characterised by *Calceola sandalina*

and *Spirifer tonkinensis*, and the Upper Devonian by *Spirifer verneuili* of the *Sinospirifer* group (Lee, 1939, pp. 121, 122, 124, 495).

The Devonian is well developed in Eastern Australia where volcanism persisted throughout. The Middle Devonian is marine and contains *Calceola* and *Stringocephalus*. In some areas plant beds containing *Lepidodendron* and *Cordaites* are found. The East Australian fauna is related to that of Dutch New Guinea, Indo-China, South China and Europe. The fauna of the Kimberley basin in West Australia has also European affinities, though the resemblance between it and that of Dutch New Guinea is not striking, which Teichert thinks may be due to difference of facies (David, 1950, p. 712). Teichert has recently recorded the presence of Middle and Upper Devonian and Carboniferous strata in the north-west basin of W. Australia (Teichert, 1949).

The barrier which separated the S.-W. China-Indo-China basin from the Himalayan basin in the Ordovician and Silurian seems to have disappeared, or largely so, in the Middle Devonian. The East and West Australian sedimentary basins were apparently connected to each other, though complete uniformity of fauna was not attained.

8. Carboniferous

The Lower Carboniferous in the Spiti area is represented by the marine Lipak series, while the corresponding formations in Kashmir are the Syringothyris Limestones. The overlying Po Series in Spiti is characterised by a *Rhacopteris* flora in the lower part (Lower to Middle Carboniferous), and marine strata with *Fenestella* and brachiopods in the upper part (Upper Carboniferous). This is paralleled in E. Australia where there was a great orogenic revolution in the Middle Carboniferous attended by effusion of lavas and intrusion of plutonic rocks.

The Upper Plateau Limestone in the Shan States of Burma shows a Permo-Carboniferous fauna with numerous brachiopods, *Fenestella* and Fusulinids, showing some affinity to the Himalayan and Salt Range regions. Marine Carboniferous strata are known in Sumatra, but the plant beds in Sumatra and Malaya contain a *Gigantopteris* flora, which shows that the land connection of these was with Indo-China and Cathaysia but not with India. In Sumatra and Central Borneo there is the Donau formation, consisting of radiolarian cherts and siliceous slates and much basic lava and pyroclastics. This formation is of Carboniferous and Permian age. In N.E. Iran also a fauna related to the Himalayan one is found, composed of brachiopods, corals and *Fenestella* in the lower and middle divisions, and Fusulinids in the Upper division.

There is a well-marked marine transgression in the Uralian (Upper Carboniferous) in many parts of the world. In the Himalayas this

transgression overlaps strata of all ages from the Cambrian to the Carboniferous, and particularly the Muth Quartzites. The Muth Quartzites are generally separated by a well marked gap from the following Productus (Kuling) Shales of Permian age. The transgression was caused by the Hercynian revolution. The Urals, Tien-Shan, Kun-Lun Karakoram, Nan-Shan, and possibly also Tsin-Lin, ranges came into existence at this time. In Ferghana, Mushketov (in Gregory, 1929, pp. 177-185) distinguishes an earlier Tien-Shan phase in the Middle to Upper Carboniferous, and a later phase in the Upper Permian. As a result of this Hercynian orogeny, a great latitudinal geosyncline was established, stretching from the Pyrenees and Alps to the Himalayas and possibly connecting through western Burma with the Banda part of the Indonesian archipelago (Timor-E. Celebes) to New Guinea and beyond Between West Sumatra and Timor, it should have lain to the south of the present chain of the larger islands. An arm of this apparently extended into Western Australia and another into the Tasman geosyncline which occupied Eastern Australia. This great Alpine-Himalayan geosyncline (the Tethys) persisted throughout the Mesozoic and was gradually dismembered during the Tertiary by the Himalayan orogeny. India at this time was part of Gondwanaland and lay much further to the south.

9. Permian

The transgressive marine Uralian passes upward into the Permian, the Uralian and the passage beds being often referred to as Permo-Carboniferous. As we have already seen, Uralian marine beds occur in Spiti and S.W. China. In the Salt Range, the Talchir tillite of Upper Carboniferous age is overlain by beds showing impressions of *Glossopteris* and spores of pteridosperms, and these by marine beds containing *Eurydesma* and *Fenestella*. These are followed by thin beds with *Conularia* and brachiopods. Similar Permo-Carboniferous beds are known in the Kolyma Province of Russia and also in Australia and South Africa. Another facies of these strata in the Salt Range is the Speckled Sandstone, though both the facies are often referred to as the 'Speckled Sandstone Group'. They are succeeded by the Productus Limestone Group, extending from the Artinskian to the uppermost Permian. The Productus Limestone facies is well developed in the Urals, Alps and Sicily.

In Kashmir, the Hercynian revolution brought about land conditions in some parts, and lavas and agglomerates (the Panjal volcanics) were erupted, commencing from the Upper Carboniferous and lasting up to the Upper Triassic. The pyroclastics are intercalated with slates containing a *Glossopteris* flora, fishes and amphibians. These Lower

Permian 'Agglomeratic Slates' are overlain in some areas by marine beds (Zewan beds) of Middle and Upper Permian age.

The marine Permian Productus Shales of Spiti continue eastwards. In the Mount Everest region and Sikkim, they are represented by the Lachi Series which is underlain by the Mt. Everest Limestone (so named as it occupies the peak) of Carboniferous to Permo-Carboniferous age. The Everest Pelitic Series below this is Carboniferous or earlier, and is profusely invaded by granite whose age has not been determined (Wager 1939).

In the Simla-Garhwal region south of the main Himalayan range the Blaini boulder beds are considered to be the equivalents of the Talchir tillites. They are overlain by the Infra-Krols (slaty shales and quartzites), the Krols (shales and limestones) and the Tals (shales and quartzites) which contain some indeterminable molluscan fossil fragments. These beds, which appear to have been laid down in shallow and perhaps land-locked waters near the margin of the Tethys, may represent the Permian and the Lower Mesozoic.

The uppermost part of the Plateau Limestone of the Shan States (Burma) contains Permo-Carboniferous fossils which are said to show some degree of affinity to those of the Salt Range.

Eastern Australia with its *Eurydesma* and *Conularia*-bearing beds shows close affinity to the Salt Range region only in the Permo-Carboniferous when the Tasman Geosyncline was connected with New Guinea. But the resemblance ceases from the Artinskian, probably because the geosyncline might have been cut off by a barrier in the region east of Queensland (David, 1950 p. 712). On the other hand, West Australian Permian fauna is more closely related to that of Timor, the Tethyan geosyncline and the Urals (David, 1950, pp. 374, 379, 398) than to the East Australian. According to Cowper Reed (1944), the affinities of the Salt Range fauna with the Russian Province became particularly strong from the Artinskian onwards but, mingled with the common fauna there is a local or endemic element in the Salt Range.

The rich marine Permian fossil assemblage of Timor, Letti, Tanimber, Ceram, Boeru and East Celebes (continuing into New Guinea) is closely allied to the Tethyan fauna. This geosynclinal belt, called the 'Banda geosyncline' by Umbgrove (1949, p. 36 and fig. 45), was in existence until the Laramide orogeny temporarily raised it up, after which, especially from the Oligocene onwards, the fauna became strongly Indo-Pacific, in common with Sumatra and Java. The Banda geosyncline was probably connected with the Tethyan through the border of Australia and through the Andamans and the Burmese arc, for there is little or no similarity in Mesozoic geology between the Banda arc and that to its

west which includes Sumatra, Java, etc. The earliest rocks seen in the Burmese arc (Axial system) are thought to be of Triassic age but we may expect the Permian also to be present underneath.

The Donau formation in Borneo, and its equivalents in Sumatra and Malaya, consist of radiolarites and volcanics (Pahang volcanics), occasionally intercalated with plant beds. Umbgrove (1949, p. 36) thinks that there were numerous volcanic islands in this region in the Permo-Trias and that the sediments were derived from the east or northeast. These volcanics extend from the Carboniferous to the Triassic. Marine Permian strata, though known to be represented in Malaya, are not wide-spread.

In South China, the Tsin-Lin geosyncline was compressed and folded in the earliest Permian. This was accompanied by lava flows in Yunnan and Kweichow. Several shallow basins came into existence and the Middle Permian shows coal seams with *Gigantopteris* flora. The marine facies, containing *Productus*, *Oldhamina*, *Lyttonia*, etc., has affinities with the Himalayan and Salt Range areas, the Upper Permian being rich in mollusca as in the Salt Range.

Coming now to the west of India, we find that in western Kashmir and Hazara there is a group of phyllites, quartzites and quartz-schists (the Tanawal series) overlying the Dogra Slates, and they may represent some part of the gap between the Cambrian and the Permian. They are overlain by the Tanakki boulder-bed which is followed by sandstones and shales and by 200 ft. of unfossiliferous massive limestones ("the Great Limestone"). This assemblage, called the Infra-Trias, is probably all of Permian age, especially as it is, in places, intercalated with the Panjal volcanics. To the south of the Salt Range, the Baluchistan arc contains some Permo-Carboniferous strata with *Productus* and other fossils.

Far down to the south, in Madagascar, we find tillites of Upper Carboniferous age followed by *Glossopteris*-bearing coal measures. There are no lower Palaeozoic rocks, as the tillites directly overlie Pre-Cambrian rocks. Above the coal measures are poorly fossiliferous Lower Permian rocks in the southwestern part of the island, but these are not represented in East Africa. The Lower Permian is succeeded, after a break, by the Upper Permian, which occurs on the mainland in the Tanga area and contains fossils which are common in the Salt Range. Since the rocks of Madagascar have a great resemblance to those of Kenya and Tanganyika, it is thought that Madagascar originally lay close to this part of East Africa. A rift between Madagascar and East Africa should therefore have developed in the Lower Permian, the sea invading this region from the north.

On the eastern side of Arabia and just south of the Persian Gulf is the Oman region, which is a structural unit alien to Arabia and belongs really to the South Persian basin of sedimentation. Suess considered the Oman ranges to be a virgation of the Zagros mountain system. Arabia (excepting Oman) is an ancient stable block practically free from mountain building movements since the Cambrian. It consists largely of gneissic rocks whose grain is roughly N-S or NNW-SSE as is also the case in Eritrea. On its west is the Red Sea rift which continues north into the Jordan Valley and the Dead Sea. This rift may have been formed in the Triassic or early Jurassic, for Triassic rocks are known in Eritrea and Jurassic rocks in the centre and along the southwest coast of Arabia. Roughly parallel to the Red Sea coast is the rift and sunken land of the Persian Gulf and the Euphrates Valley, which are of recent origin.

In the Oman region, there is only a small area exposing Cambrian rocks (Hormuz series) similar to those of the Salt Range. They are overlain by pre-Permian phyllites and by Permian, Jurassic, Cretaceous and Eocene sediments. All the rocks, up to and including the Lower Cretaceous, are invaded by the Semail igneous suite which are mostly basic in character, but include also serpentines, granites and diorites which must have been emplaced in the Middle Cretaceous (pre-Gosau or pre-Maestrichtian) according to De Bockh, Lees and Richardson (in Gregory, 1929).

The pre-Permian rocks of Oman contain limestones, shales and intercalated lavas, the associated fossils being indeterminable. On the southwest side there is a quartzite formation, also pre-Permian. These are succeeded by dark limestones of Permian age containing fossils closely related to those of the Middle Productus beds of the Salt Range. In Central Oman, there are sheared limestones containing a different fauna. These are followed by Triassic rocks.

In the Elburz mountain and Gulshan regions in Northern Iran Permian rocks having affinities with those of the Himalayan region are known (Clapp, 1940).

10. Triassic

The Triassic is well developed in the Spiti area and consists of the Chocolate series (Scythian), the Kalapani Limestone (Anisic, Ladinic, Carnic), Kuti Shales (Noric) and the Kioto Limestone (Rhaetic). The uppermost portion is a massive limestone (*Megalodon* or Kioto Limestone) which is mainly Rhaetic and partly Lower Liassic. The deposits in Kashmir are also similar.

In the Burmese arc the Triassic is represented by the lower part of the Axial system, which may be Upper Triassic. But these formations have not been investigated in any detail. In the Shan States there is a hiatus between the Plateau Limestone (Lower or Middle Permian) and the Rhaetic, which latter is characterised by shallow water deposits containing gastropods, lamellibranchs and corals. In the Red Basin of Szechuan, the Lower Triassic is a dolomitic limestone associated with rock-salt. But in Yunnan, marine fossils with Tethyan affinities are found. The sea receded in the Upper Triassic when mountain building movements affected China and Indo-China, Borneo and West Celebes.

In Malaya, Sumatra and Borneo, the Triassic includes marine deposits other than the radiolaria-bearing cherts. But a full succession with rich marine fauna of Tethyan affinities is developed in the Banda geosyncline. Triassic rocks have not so far been recorded from New Guinea. East Australia was a land of lakes during this period and the deposits contain a *Thinnfeldia* flora which replaced the *Glossopteris* flora more or less completely. In west Australia also, the geosyncline had receded to the west and land conditions prevailed.

In Kashmir, the full Triassic succession is met with in the Sind-Lidar valleys, central Ladakh and the Pir Panjal, but only the Upper Triassic is seen in the north-west and in Hazara. Here, the Lower Triassic is represented by the Panjal volcanics. Further south, in the Salt Range, the Lower Triassic and the lower part of the Middle Triassic are seen, but still further south, only the Upper Triassic is developed. In the Zhob-Pishin (Quetta) region of Baluchistan the Upper Triassic occupies an area 70 miles long (E-W) and 10 to 12 miles wide.

Except for local development of the marine Triassic, Madagascar shows mainly lacustrine and continental deposits (Isalo Sandstone). Land conditions prevailed also in parts of E. Africa, and in Central and South Africa. In may areas in Gondwanaland the Upper Triassic is transgressive over the Lower or Middle Triassic (Dixey, 1935), while the close of the period is characterised by extensive volcanism in the southern part of Africa.

In the Oman region of Arabia, Upper Triassic rocks overlie the Permian unconformably. They are composed of yellow sandstones, shales and thin limestones with mainly molluscan fossils. In S.W. Iran also the Triassic unconformably follows on the Permian, but the deposits contain a larger variety of fossils as in the Himalayas. In North Iran again, the Lower Triassic is missing and the Upper Triassic is a massive limestone characterised by brachiopods, gastronods and lamellibranchs (*Daonella, Pseudomonotis, Megalodon, etc.*), but few cephalopods recalling the conditions in the Himalayas,

The land conditions in the Lower Triassic, especially in the areas bordering the southern arm of the Tethys and in Madagascar and East Africa, indicate a marine regression probably resulting from the widening of the Arabian Sea-Mozambique Channel rift. This was followed by a transgression in the Upper Triassic.

11. Jurassic

In the Spiti area and N.W. Kumaon, the marine *Megalodon* Limestone continues without interruption into the Laptal series of Liassic age, characterised by layers of broken shells (lumachelle). This is overlain by a conspicuous oolitic bed of Callovian age known as the *Sulcacutus* bed which is a well-marked horizon, but the junction is marked by a discontinuity. The Callovian bed is followed by another discontinuity extending up to the Oxfordian or Kimmeridgian, when the ' Spiti Shales ' began to be deposited. The same is the case in the Ladakh area of Kashmir also. In some places the Callovian unconformity extends up to the top of the Jurassic.

Jurassic rocks continue eastwards to Sikkim and occupy a large area in Tibet. On the Tibetan frontier of Kumaon (Punjab Himalaya), in the Chitichun—Kiogad area, there are large isolated masses of limestone resting on and surrounded by Cretaceous flysch sediments and andesitic and basaltic lavas and intrusives. These limestone blocks have yielded marine fossils of Permian, Triassic, Jurassic and Cretaceous ages and are of a facies different from that of the Spiti rocks, but closely resembling the Dachsteinkalk and the Hallstatt marble of the Eastern Alps. These are the ' exotic blocks ' of Malla Johar described by Diener (1898) and by Von Krafft (1902). It is thought that these blocks were brought to their present position from the north either by floods of lava of Cretaceous age or by thrust-sheets or *nappes*. Heim states (1937, p. 445) that the ' exotic ' region is the result of weathering of the thrust sheets derived from Tibet and that the Triassic rocks of the Kiogad peaks were noticed by him to extend for an unknown but large distance to the north-east. Heim and Gansser (1939, pp. 160-161) have given reasons to show that the exotic blocks and associated rocks are the remnants of great thrust-sheets which have travelled south-westwards from Tibet and include rocks of both Himalayan and Tibetan facies. The roots of these are in the similar zone of exotics of Darchen region south of Mount Kailas. In the Mt. Everest region, the facies is similar to that of Spiti; but in the Lesser Himalayas of Garhwal a part of the Infrakrol-Krol-Tal succession, which is either practically unfossiliferous or contains only fragmentary fossils, may be of Jurassic age.

The presence of Jurassic rocks has not been definitely recorded in the Burmese arc, but the Axial system and associated strata should

reasonably be expected to include these as they have been proved to contain both the Triassic and the Cretaceous.

The Namyau beds (red sandstones, shales and limestones) of Northern Shan States are of Bathonian age while the Loi-An beds of Southern Shan States contain Jurassic plants and coal seams. In Tenasserim on the Siam border, there are red sandstones, etc., lithologically similar to the Jurassic of Northern Shan States, Siam and Tonkin. The Shan area is connected through Yunnan to the Szechuan Red Basin near which fresh-water deposits with coal seams occur.

The end of the Jurassic was marked by the late Cimmerian orogenic activity in China, which raised up the Yen-Shan and Cathaysian ranges. It also affected Borneo, west Celebes and Malaya. The granites of Malaya, Tenasserim, Siam and Burma are generally assigned to this age (Scrivenor, 1931).

The Banda geosyncline as well as New Guinea show Jurassic rocks. In the latter, the Jurassic appears to be all post-Callovian.

In West Australia there are lacustrine sediments with plants of Rajmahal age. Marine transgressions occurred in the Middle Jurassic. A fauna of Tethyan affinities of Bajocian age has been found near Geraldton, and of Oxfordian age from boreholes at Broome (Teichert, 1940; 1947).

Coming now to the western side of the Tethyan geosyncline, we find two facies lying side by side in Hazara. The northwestern facies (the Kioto Limestone—Spiti Shale type) shows a break between the Bathonian and Oxfordian but the strata above the Oxfordian seem to be unfossiliferous until we come to the Albian (Cretaceous).

The Middle and Upper Jurassic are developed in the Salt Range. In the Samana Range, the Lower Jurassic is succeeded by the Upper Jurassic, with a break between the Callovian and the Oxfordian. In Eastern Baluchistan, the Liassic beds are succeeded by massive limestone which indicates deposition up to the Callovian. After this there is a break until the Neocomian.

Marine limestones and sandstones are seen in the Jaisalmer and Bikaner areas of Rajputana, ranging up from the Callovian. The full extent of these beds is not known, being partly hidden by desert sands.

In Cutch, on the western coast of India, there is a fine development of marine Jurassic strata ranging from the Bathonian to the top of the Jurassic and extending to the Aptian, with intercalations of plant beds of Neocomian age. It is thought that the basin of sedimentation deepened gradually as sedimentation went on. The fauna is rich in cephalopods, allied closely to those of the Salt Range and the Himalayas (Spath, 1933). Marine Jurassics are not exposed in central or western India though fluviatile and lacustrine Upper Gondwanas are found.

Jurassic sediments were laid down also at some places on the eastern coast of India where plant-bearing beds are associated with shallow-water marine beds. Some poorly preserved ammonites from these beds have been assigned a Neocomian age by Spath (1933, pp. 827-829). In the Rajmahal area, at the head of the Ganges delta, a few plant beds are associated with 2,000 ft. of basic lavas, while basic and ultrabasic dykes of the same age traverse the coal-bearing Barkars of the eastern coal-fields. Lava flows, presumed to be of the same age, are also seen in the Assam Plateau and in the Abor Hills in the Eastern Himalayas.

It will be clear, therefore, that the eastern coast of India definitely took shape sometime during the Jurassic period or towards its end, while the Cutch-Southern Rajputana region was inundated by the sea in the Bathonian and Callovian.

An interesting fact to which reference may be made is that, while there is a sedimentary break from the Callovian to the Oxfordian or Kimmeridgian in the Himalayas and in the Baluchistan arc, sedimentation commenced in Cutch in the Bathonian and proceeded uninterrupted until the Aptian. In Rajputana also, so far as known, there was sedimentation from the Callovian to the end of the Jurassic. Hence, in the Callovian, while the sea temporarily regressed from the margin of the main Tethyan basin, it transgressed over Rajputana and the western coast of India.

Jurassic rocks are well developed along the coast of Madagascar and East Africa and also in Somaliland, southern coast of Arabia and Central Arabia. In East Africa, however, they have not been found south of Lindi (Du Toit, 1937, p. 124) which probably shows that the Mozambique rift had not opened up beyond this in the Jurassic. The marine fauna of these areas is similar to that of Cutch. During the Middle Jurassic there was folding in Madagascar along a N-S axis, accompanied by faulting, which according to Du Toit (1937, pp. 123-124) was due to an anti-clockwise twist and movement of the island. The Rift Valleys of East Africa may have been formed also at this time.

In the Oman region, the Upper Triassic is overlain by the Mussandam Limestone, 5,000 ft. thick, containing Neocomian fossils at the top and therefore mainly of Jurassic age. In Southern Iran, the Lower Jurassic is non-marine but the Middle and Upper Jurassic are closely related to the strata of Cutch and the Salt Range.

12. Cretaceous

Cretaceous strata occupy large areas in the Himalayas and Tibet. In Spiti the Lower Cretaceous is represented by yellow glauconitic sand

stones and slaty quartzites called the Giumal Sandstone, the youngest part of which is Albian. They are overlain by the Chikkim series—grey and white limestones and shales—containing *Belemnites*, *Hippurites*, and foraminifera. Above these are flysch-type sediments. The Himalayan Cretaceous (especially the Lower and Middle Cretaceous) strata show evidence of a shallowing of the sea and a distinct change in fauna, because of the invasion of Mediterranean fauna probably through Syria and Southern Iran. The shallowing may be attributed to the withdrawal of water from the Tethyan basin to the Indian Ocean due to the breaking up of Gondwanaland and to mountain-building movements which took place during the Middle Cretaceous in parts of the Tethyan basin. There are no Tertiary strata known in the Spiti-Kumaon region.

In Malla Johar, Lower Cretaceous shales are overlain by flysch sediments. These include black flysch, red and green siliceous deposits and radiolarian oozes of late Cretaceous age, deposited in deep sea under geosynclinal conditions (Heim and Gansser, 1939, pp. 213-214). They are associated with volcanic breccia and some intrusions which are over 1,000 ft. thick, and in which huge blocks (exotic blocks) of fossiliferous marine rocks of all ages from the Permian to the Cretaceous lie pell-mell. These volcanics are of Upper Cretaceous age. Passing on to Kampa Dzong in Tibet, we find a full Cretaceous sequence, but it is not clear whether there is a break below the Cenomanian, for the pre-Cenomanian limestone is unfossiliferous. The Cenomanian and later strata are fossiliferous and pass upwards into the Eocene.

In the Burmese arc, Cenomanian and Upper Cretaceous fossils have been found both in the Axial System and in the Negrais series in the Arakan region. These include species of *Schloenbachia* and *Acanthoceras* characteristic of the Cretaceous of Trichinopoly, Madras. It is not known to what extent the Lower Cretaceous rocks are represented. At several places along this belt, peridotites and serpentines of Upper Cretaceous age are found—Jade Mines area, the Naga Hills, the Manipur Hills, Arakan region, and the Andaman-Nicobar Islands (*see* p. 74). *Orbitolina*-bearing limestones are found in Upper Burma while Upper Cretaceous red beds occur in Southern Shan States. Similar red beds are found in Szechuan in S-W China.

Malaya remained a land area during the Cretaceous while Borneo and Western Celebes contain Cretaceous sediments laid down during the Cenomanian and Senonian transgressions. Sumatra and Java also show Cretaceous rocks in some places.

The Banda geosynclinal belt continued to receive marine sediment throughout the Cretaceous. New Guinea also contains Cretaceous sediments, but it is not known whether any of these is younger than the Cenomanian (David, 1950, p. 670). The Banda geosyncline and New

Guinea were severely folded and raised temporarily above the sea in Laramide times. This movement affected also Sumatra and Java but the Borneo-West Celebes region lying to the north of the geosyncline was only mildly affected.

Marine beds are developed in West Australia from the Aptian onward and the fauna is closely allied to the Cretaceous of Trichinopoly in Madras, of Assam and of Madagascar. That is to say, the West Australian geosyncline was directly connected to the Bay of Bengal in the Aptian and the already weakening Tethyan faunal element was swamped by the Indian Ocean fauna.

Marine Cretaceous strata are found in the Trichinopoly district of Madras and on the Assam plateau. In the former, sedimentation began in Upper Albian and continued into the Eocene. On the Assam plateau the Cenomanian beds lie over the Archeans and they must originally have occupied a large area, as shown by the scattered outcrops. Beds with similar fauna occur also on the eastern and western coasts of Madagascar in Tanganyika and Mozambique. This sea extended southwards into Argentina. The occurrence of reptilian remains of closely allied species in India, Madagascar and Argentina indicates, according to Du Toit (1937, p. 124), that India and Madagascar were connected together until the Middle Cretaceous, for it is only in the Middle and Upper Cretaceous that marine sediments were laid down on the east coast of Madagascar. At about the same time, some Mediterranean faunal elements entered the Indian Ocean. India and Arabia then began to drift northeastwards as a result of which the sediments of the Oman and Tethyan regions were subjected to folding in the Middle Cretaceous.

The north-eastern coast of Africa is marked by the Rivu-Mombasa and the Lindi-Mafia-Zanzibar faults which converge together (Du Toit, 1937, p. 125). As already indicated, they may have been developed gradually from the Upper Permian onwards. The dyke swarms of Eastern Madagascar and some of the volcanic rocks associated with the Rift system of E. Africa are thought to be of Cretaceous age.

In the Astor-Burzil region of Kashmir, Cretaceous sediments are intercalated with basic volcanics and intruded by serpentines, pyroxenites and granites. In the north-western zone of Hazara, there is a sedimentary break above the Albian and again at the base of the Eocene. The Calcareous zone (south-eastern) shows a similar break above the Albian but the break is said to continue into the Lower Eocene. This is repeated in the Salt Range where, however, Maestrichtian foraminifera have recently been found in strata which were regarded as Jurassic (Rao, S.R.N. and Tripathi, 1950). The unconformity in the Calcareous zone of Baluchistan may therefore be taken to extend from the Albian to the Senonian. The Cretaceous fauna includes *Inoceramus* and Rudistids,

indicating admixture with Mediterranean elements. The Upper Cretaceous is intercalated with basic volcanics and intruded by peridotites and serpentines with chromite deposits in the Hindubagh area near Quetta.

Cutch shows continuous marine sedimentation from the Jurassic up to the Aptian, after which there is a break, followed by the Deccan Trap flows, and these by Lower Eocene. In the Narbada Valley in Western India, Cretaceous strata begin only with the Cenomanian and continue into the Eocene. The fauna of these strata is more allied to that of Baluchistan and Arabia than to that of the eastern coast, though there are some common elements.

In Eastern and Northern Iran there is generally an unconformity in the Aptian-Cenomanian. An Aptian overlap is seen in South Central Iran and the strata from the Cenomanian upwards are mainly limestones containing Rudistids, Trigoniae, etc. The upper Cretaceous is characterised by lavas (rhyolites, porphyries and basalts) overlying the Hippurite limestone. These are followed by Maestrichtian and Eocene strata.

The Jurassic to Neocomian Mussandam Limestone of Oman is succeeded, after an unconformity, by strata of the Hawasina series consisting of sandstones, Rudistid limestones and red and green radiolarites associated with thick lava flows and intrusions of granite, diorite and peridotite (the igneous rocks being called the 'Semail group'). The Jurassic fauna of Arabia is related to that of Cutch and the Salt Range but not to that of Syria and Sinai; on the other hand, the Cretaceous fauna shows resemblances to the latter areas through which the Mediterranean elements must have entered the Indian Ocean.

The Oman region is highly folded and contains peaks as high as 10,000 ft. The range in the north runs NNW-SSE but turns south towards Masirah and Ras Madraka where the rocks run into the sea in a W.S.W. direction. The period of folding is pre-Maestrichtian (pre-Gosau) according to De Bockh and others (Gregory, 1929). There is little doubt that the rocks of the fold belt turn east and northeast after entering the sea, to join up with the Baluchistan ranges. The period of folding may be represented by the stratigraphical gap of the Aptian-Cenomanian which extended up to the Maestrichtian in Oman and to the Campanian in Beluchistan. It would appear that the folding movements continued into and affected the Baluchistan arc. As the Jurassic-Aptian succession in Cutch is also folded before the Deccan Traps were erupted late in the Upper Cretaceous, it might also have been folded at the same time—*i.e.*, in the Middle Cretaceous. That the Cretaceous folding movements affected the Baluchistan arc and even part of the Himalayan Tethyan basin finds support in the presence of Upper Cretaceous ultrabasic and other igneous rocks at some places in Baluchistan, Kashmir and the belts of exotic blocks of Kumaon and Tibet.

On the other side of India, in the Burmese and Banda arcs and in New Guinea, mountain building took place in Laramide times, when the Burma-Assam sea was divided into two gulfs separated by the newly risen Assam-Arakan ridge. The Middle Cretaceous movement in the Baluchistan arc and part of the Tethyan basin in the Himalayas should therefore be treated as the earliest of the Himalayan movements which had full play in the Tertiary. In accordance with the theory of Continental Drift, the Middle Cretaceous should be the time when the north-eastward drifting India encountered and began to crumple up the Tethyan geosynclinal basin.

It has already been stated that the Oman region does not belong to the Arabian mass but is really a geosynclinal area subjected to mountain building movements in the Cretaceous epoch. Arabia was severed from Africa probably in the Upper Triassic, since Liassic sediments are known along the southern coast of Arabia. In its north-easterly drift, Arabia encountered the Oman basin, just as the Indian shield came up against the Tethyan basin. The Cutch-Narbada valley area was a minor basin, on the border of India, which also suffered folding as a result of the same drift.

13. The Deccan Traps*

The Deccan Traps now occupy some 200,000 sq. miles and must have formerly covered a more extensive tract, probably twice the present area. They are regarded as having been erupted from numerous fissures in the crust during a period of tension. They are estimated to have a thickness of over 6,000 ft. near the Western Coast (Oldham, 1893, p. 262), but much less in other areas. They must originally have extended also for an unknown distance to the west of India but that part was faulted down in or about the Miocene.

Geologists in India generally include the basic lavas on the Sind-Baluchistan border with the Deccan Traps, but as they are in the fold-belt of the Baluchistan arc and occur as intercalations in Upper Cretaceous strata, it would be better to exclude them from the Deccan Traps proper.

In Cutch, Kathiawar and Gujarat, the Traps appear to be of the uppermost Cretaceous to the earliest Eocene age. In Cutch, where they are 2,500 ft. thick (Wynne, 1872, p. 60), they have been exposed to sub-aerial weathering and denudation, with the alteration of the topmost layers to laterite before the Nummulitic Laki Series (Upper division of Lower Eocene) was deposited over them. Blanford (1869, p. 62) has stated that near Tarkeser in Broach (Gujrat) there is an unconformity between the Traps and the Lower Eocene, and that the latter contains pebbles and detritus derived from the former (Oldham, 1893, p. 282).

* The Deccan Traps, confined to the Peninsular region, are discussed here for descriptive convenience.

In the rest of the area occupied by the Traps, they are considered to be of Eocene age from the study of plants, fishes and foraminifera found in the Inter-trappean sedimentary beds (B. Sahni, 1940 ; Hora, 1938).

There are several eruptive centres in Kathiawar and the Narbada Valley, from most of which acid volcanics have been erupted while two of them contributed plutonic intrusives also. They are roughly aligned ENE—WSW in the Narbada Valley but the line connecting the centres curves towards the WNW in Kathiawar. The age of these eruptions must be later than that of the main mass of the Traps.

Dyke clusters are confined mainly to two rectilinear zones—one along the Panvel flexure parallel to Bombay coast, and the other along and parallel to the Narbada rift—and to an elliptical area around Amreli in east-central Kathiawar. The first two are connected with fold or fracture zones while the third is supposed to be a domed up area in which peripheral and radial fractures played an important part in the formation of dykes. They have been described recently by Auden (1949). The dykes are mostly later than the Traps though there must be many, in these and other areas, which acted as feeders to the Trap flows.

The Traps were erupted and spread over an uneven pre-existing topography. Their base is now found at different levels above or below sea level : at 2,000 ft. above sea level at Belgaum ; 1,000 ft. near Nagpur ; at 1,600 ft. on the flanks of the Maikal range ; at 2,500 ft. south of Sohagpur and in the Ranchi Plateau ; and at or over 3,000 ft. in Jashpur (Auden 1949, p. 321).

But at some places near Bombay, in the Narbada Valley and in Kathiawar, their base lies 500 to 1,800 ft. or more below sea-level, as a result of folding and faulting.

They lie with a profound unconformity on all pre-existing rocks and sometorne their margin may be seen transgressing over a series of formations as in Southern Rajputana, Central India, south of Pachmarhi and Sohagpur, etc. They must originally have extended at least as far east as East Longitude 85°. In some areas, the Gondwanas over which they lie have been folded before they were erupted and it is possible that the period of folding was the Middle Cretaceous which affected the Cutch area and which possibly extended into the Narbada-Son Valley.

The Traps have themselves suffered folding and faulting at a later date. Gentle warping has been noted in the Traps of Chindwara by Fermor and Fox (1916, p. 81). In Rajpipla in Gujarat, at the western end of the Satpura mountains, the Traps are sharply folded along ENE—WSW axis and dips of 20° have been noted (Blanford, 1869, p. 57). Folding is well seen along a zone bordering the Narbada Valley in the Central Provinces (Crookshank, 1936, p. 265, etc.). The Panvel flexure,

which extends from Panvel (18°59′ : 73°07′) to Kalyan near Bombay in a S-N direction and then turns NNW to the coast near Daman, is a monocline, the western limb of which dips at 10° into the sea. In south-eastern Kathiawar the Traps show dips of 10° towards the southeast while in Cutch they have been folded into well marked anticlines and synclines. In most other areas the flows are practically horizontal. The period of folding may be either the end of the Eocene or the Middle Miocene.

Faults are known to have affected the Traps in some places. The south side of the Narbada rift has been faulted down some thousands of feet (Crookshank, 1936, pp. 261, 265, 286) in relation to the Traps on the Pachmarhi side. The Ellichpur fault running by the side of the Gawilgarh Hills shows a downthrow of a minimum of 1,800 ft. and a maximum of perhaps 4,000 ft. (Fermor, 1930, p. 409). There is a post-Trap fault to the north of the Satpuras of the Pachmarhi area (Crookshank 1936, pp. 276, 287). The Bombay coast is itself a fault scarp of probably Miocene age, the downfaulting being of the order of 6,000—7,000 ft. The different faults may have originated at different times.

The Aravallis must have been cut across along the Narbada region (and probably across to Cutch) in the Middle or Upper Carboniferous, thereby enabling an arm of the sea to reach Umaria in Lower Permian times. This remained a zone of weakness afterwards, for folding and faulting continued to affect it until geologically recent times. The basin of the Purna tributary of the Tapti shows Pleistocene sediments containing salt water to a depth of at least 120 ft. which is thought to be due to the sea extending here during the Pleistocene (Oldham, 1893, p. 401).

14. Eocene

The Tertiaries of the Himalayan region can be divided into three periods of sedimentation, each culminating in an orogenic movement. The three periods are the Eocene, Oligocene to Middle Miocene and Upper Miocene to Pliocene. The corresponding formations are the Eocene, the Murree and the Siwalik. The orogenic activities at the end of each of these periods are generally referred to respectively as the first, second and third phases of Himalayan upheaval. There is reason to believe that there was an earlier movement in the Middle or Upper Cretaceous as mentioned already, and later movements in the Pleistocene and sub-Recent times (De Terra, 1936). The history of the Burmese Tertiary is roughly similar to that of the Western Himalaya, but a difference is discernible in the Assam Tertiaries formed in the gulf which existed to the west of the Burmese arc. In Assam, the Barail and Jaintia series extends from early Eocene (or even Upper Cretaceous)

to the Middle Oligocene, when a wide-spread unconformity occurs. The succeeding Surma series and Tipam series are roughly Oligocene to Lower Miocene and Middle Miocene to Upper Miocene, respectively. A second important unconfoımity occurs in the Upper Miocene, succeeded by the coarse sediments of the Dihing Series of Pliocene age.

The Eocene comprises three distinct facies—a deep sea facies in the Calcareous zone of Baluchistan, Northern Kashmir and the Tibetan zone of the Himalayas (which extended at least as far east as the meridian of Lhasa in Lower Eocene), and also in parts of the Burmese arc; a shallow facies on the southern side of the main Himalayan range as far east as Naini Tal and in Cutch, Gujarat, S.W. Rajputana, and the southern border of the Assam plateau; a *flysch* facies in parts of the Himalayas and in Baluchistan. There was also a fresh water facies in N.W. Punjab and in Upper Burma.

The Laramide orogeny raised the East Indian archipelago (particularly the Banda arc) and New Guinea into land temporarily and land connection was probably established between S.E. Asia and Australia for a short time. The sea transgressed again over this arc and over Western Celebes and parts of Borneo in Lower Eocene. There was still a strong Tethyan element in the fauna of the East Indies and New Guinea during the Eocene (David, 1950, p. 709). But at the end of the Eocene, the Tethyan element disappeared and the Indo-Pacific fauna, which was already prominent in Madras, Assam, Madagascar and W. Australia in the Cretaceous, established itself in the East Indies and New Guinea basins.

In Oman, both fossiliferous marine facies and the *flysch* facies are developed in the Eocene, the fauna of the former being similar to that of Baluchistan. The Eocene extends into and occupies a large area in Central Arabia. In Eastern and South-eastern Persia there are thick basic volcanics, pyroclastics and some intrusives commencing from the Middle Eocene and continuing into the Oligocene. The marine fauna closely resembles that of Baluchistan. In S.W. Iran the Lower Eocene is of shallow origin, characterised by red marls and gypsum.

15. Oligocene—Lower Miocene

The orogeny at the end of the Eocene broke up the Tethyan geosyncline into shallow basins. The Baluchistan and Burma areas were however, connected with each other through the Indian ocean and fossiliferous open-sea sediments as well as those of the *flysch* type continued to be deposited therein. On the southern side of the Himalayas, the Murree System of brackish water sandstones was deposited in the

Punjab and Kashmir and for some distance further east. Marine deposits were also formed in Southern Cutch and in Gujarat.

In southern and south-western Iran, the Oligocene is represented by the Asmari Limestone (marine) and the Fars Series (lagoonal), the latter showing deposits of saline marl, gypsum and anhydrite. In Arabia, the Oligocene and Miocene are developed in restricted areas and are of shallow facies.

There was sedimentation in the East Indies all along the outer arc (Nias-Mentawei strip and the Banda geosyncline) as well as in parts of Sumatra, Java, East Celebes and Borneo. The fauna is Indo-Pacific in character.

16. Middle Miocene—Pliocene

Towards Middle Miocene, intense orogenic forces affected the Himalayan, Baluchistan and Burma arcs and considerable uplift and thrusting took place. Granites, and possibly also other igneous rocks were extensively intruded along the main Himalayan belt.

The unconformity below the Middle Miocene (Miocene—e4, of Umbgrove, 1949, p. 40) seen in many areas in the East Indies is probably the effect of the Himalayan orogeny. In Upper Miocene (Miocene—f2) intense folding and thrusting took place in Southern Sumatra and the inner arc, as well as the entire outer arc, and especially in the Banda geosyncline and New Guinea (Umbgrove, 1949, p. 41, fig. 50). The overfolding and thrusting came from the north in the Banda arc and from N. E. in New Guinea.

The deposits of this period are found all along the foot-hills of the Himalayas, in Potwar and Jammu areas, in Sind, in the Burmese Tertiary belt and on the Assam side of the Burma arc. They constitute the Siwalik System and its equivalents which are generally composed of coarse fluviatile sediments. Their great thickness (of the order of 16,000-18,000 ft.) along the border of the Himalayas shows that they were formed in a shallow depression which was gradually sinking, the recently risen mountains being the source of the sediments.

The Siwaliks were folded and thrust over by older rocks, probably at the end of the Pliocene ; in their front, along the margin of India, a fore-deep went on forming. This fore-deep is now the valley of the Ganges and Brahmaputra, filled with thick Mio-Pliocene, Pleistocene and Recent sediments. Movements of some magnitude took place also in the Pleistocene, for we find that the Karewas of Kashmir have been raised up several thousands of feet on the slopes of the Pir Panjal and that certain beds enclosing Palaeolithic remains have been tilted and lifted to a height of 4,500 ft. (de Terra, 1937).

Marine Mio-Pliocene rocks are found in Baluchistan, on the east and west coasts of India, in northern Ceylon and in the Arakan area. The fauna is similar to that of Java and other islands of the East Indies.

In Eastern and Southern Iran, the Upper Miocene and Pliocene beds are represented by the Upper Fars and Bakhtiari beds which are shallow water deposits, the latter resembling the Siwaliks. The Middle Pliocene is highly folded, and the eroded Bakhtiari beds are overridden by nappes which may be of Upper Pliocene or Pleistocene age.

The Upper Tertiaries in Arabia were gently folded in Upper Miocene or Pliocene and subjected to faulting and uplift. Along the Oman coast, downfaulting occurred probably in Pliocene or later, because of which the trend of the formations is abruptly truncated. The northward projection in Oman on the Persian Gulf Coast and the corresponding kink on Iranian side of the same Gulf is due to an extension of the Oman Range into Iran. Rocks of the Hawasina series are found in a few places in the Zindan nappe north-east of Bandar Abbas. The Oman folding (Cretaceous), however, affected the South Persian geosyncline very little, and in any case the full Tertiary succession in Southern Persia has obscured a good deal of the previous structures present there. This geosyncline began to develop in the Jurassic and therefore most of the deposits are later than the Middle Cretaceous Oman orogeny. In this area, the autochthonous belt is followed, to the north, by an 80-mile-wide nappe zone containing three nappes, which successively bring up older rocks over the younger. The overthrusts are directed from the north-east towards the south-west. An uplift is known to have occurred in pre-Maestrichtian, probably during the Oman orogeny, for there are thick Maestrichtian conglomerates here. The Miocene is transgressive over older rocks. The Mid-Miocene Bakhtiari beds were uplifted and eroded before the violent folding of the Pliocene, which was probably continued into the Pleistocene. Finally, the folded rocks were elevated and the Persian Gulf-Euphrates Valley region depressed or faulted down. This may be of the nature of a 'fore-deep' between the Arabian mass and the Tertiary fold-belt of the Zagros mountain system. The northern shore of the Persian Gulf shows fault scarps of Pleistocene or Post-Pleistocene age in several places. (De Bockh and others; in Gregory, 1929.)

MOVEMENTS IN INDIA DURING THE TERTIARY

It is generally recognised that after the Jurassic there was an uplift and erosion before the Cenomanian transgression took place. The period of uplift may be just after the Neocomian. The Cretaceous sedimentation apparently continued into the Eocene, as Eocene foraminifera have been recorded from the Pondicherry area. In Gujarat and Cutch, the Laki Series (Lower Eocene) is found to be transgressive over the Cretaceous. There was again a well marked transgression in or about the Middle Miocene, especially along the southwestern, and all along the eastern, coast. Minor epeirogenic oscillations have occurred in the Pliocene and Pleistocene times also, as evidences are found in raised beaches, submerged coasts, etc.

The Assam plateau is considered to be a *horst* uplifted in the Miocene. It is bordered on the north by a fault showing a prominent scarp. On the southern side, the western portion is a fault which, when followed eastward, becomes a monocline and further on merges into the Haflong-Disang thrust fault with overthrust from the Burma side, this thrust fault continuing in a north-easterly direction into Upper Assam. There are several parallel thrust zones in the Patkoi-Naga-Manipur-Lushai Hills which represent thrust movements from the Oligocene or Miocene onwards. The western side of the Assam plateau may also be marked by fracturing which may be connected with the Garo-Rajmahal gap through which the Ganges and the Brahmaputra now flow southwards to sea.

The Himalayan orogeny produced a 'fore deep', a down-buckling of the crust to form a trough in front of the folded mountains. The various stages of the movement would have accentuated this basin. It would appear that the southern arm or flank of this synclinal trough suffered elevation at each stage. Four regional uplifts have been noted in Chota Nagpur, Bihar, which are, according to Dunn (1939, p. 141) :—

1. Lower Tertiary uplift of 1,000 ft.
2. Middle Tertiary (Mid-Miocene ?) uplift of 1,000 ft.
3. A further uplift of 300 ft.
4. A still later uplift of 400 ft.

The total uplift was therefore of the order of 2,500-2,700 ft. This is best seen in the Ranchi plateau along North Latitude 23°. But it is interesting to note that along latitude 25° there was practically no

movement, this being of the nature of a hinge zone located somewhere in the middle of the southern limb of the trough. The movements are shown diagramatically below. (Fig. 12).

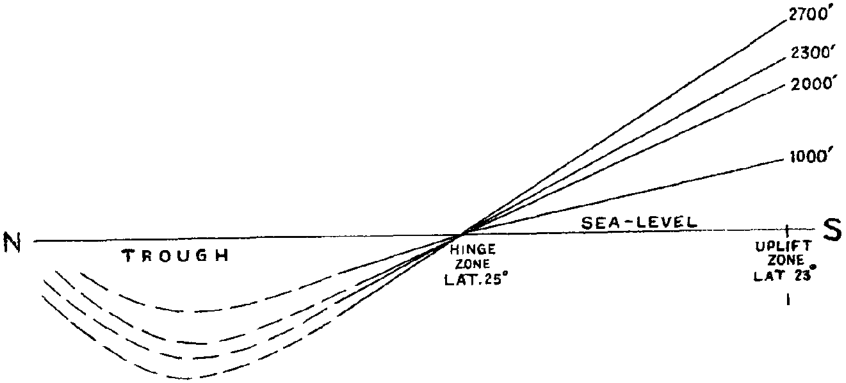


Fig. 12.

THE EASTERN COAST AND THE BAY OF BENGAL

The eastern coast in Orissa and northern Madras down to the Kistna Valley is parallel to the Eastern Ghats. Then it turns south, accommodating itself roughly to the Archaean and Cuddapah rocks which here show southerly to SSE trend a little to the north of Madras. The coast more or less maintains its southerly trend, with a slight easterly convexity in the Nellore region, up to the Cauvery delta, though the rocks turn sharply towards the S. W. and WSW near Madras city. In the southernmost part of the Peninsula, the coast has a south-westerly trend down to Cape Comorin, but here it is practically perpendicular to the strike of the rocks.

The earliest marine sedimentary rocks along this coast after the Cuddapah-Vindhyan times occur in the Middle or Upper Jurassic amongst the Upper Gondwana rocks of Guntur and Kistna districts. Though similar plant-bearing upper Gondwanas are known to occur in Orissa and Southern Madras, they do not seem to be associated with any marine intercalations. Neither are marine strata associated with the Tabbowa beds of the north-west of Ceylon. It is, therefore, clear that the eastern coast of India took shape during the Jurassic.

The West Australian geosyncline seems to have been formed in the Devonian. The incipient Bay of Bengal of Jurassic times was probably directly connected with it, since evidence of such direct connection is available in the Cenomanian fauna being very similar in both the Trichinopoly area in Madras and in the West Australian geosyncline. The Upper Cretaceous fauna of Madagascar and East Africa are also similar so that we can assume that, at that time, the Indian Ocean lapped the shores of all these lands. Ceylon seems to have been first severed from India in the Middle or Upper Miocene for it is only at that time that marine beds (Jaffna beds) were formed on the north-west and north of Ceylon (Jacob, 1949, p. 341). Thereafter connection and severance took place a few times, and the sea separating the two is very shallow and supports numerous coral islands.

Proceeding now to the eastern part of the Bay of Bengal, we have already seen that the sea extended, in the Cretaceous, over a large part of Assam and Burma. A ridge was raised up by the Laramide orogeny along what is now the axis of the Burma arc and the two arms thus created were gradually filled up during the Tertiary. The connection of the Burmese sea with the Himalayan one probably ceased about this time or. at any rate, at the end of the Eocene.

It would thus appear that the Andaman Sea (*i.e.*, the basin between the Burma-Andaman-Sumatra arc and Tenasserim-Malaya) took shape at the end of the Cretaceous (Sewell, 1925). The eastern border of this basin is regular and is marked by the submerged ridge bordering the Mergui Archipelago. The Andaman Sea basin connects with the Sunda Sea through a channel coursing through the Straits of Malacca. Sewell has suggested that this channel may be a drowned river valley. The western border is less regular and consists of a mountain chain 700 miles long, a few peaks of which rise above sea level. The mountain chain is really the Andaman-Nicobar part of the Burma-Sumatra arc and it shows Cretaceous and early Tertiary sediments (and recent coral limestone) with some serpentine intrusions (Tipper, 1911). The basin was probably a shallow sea originally, but faulted down later to its present depth. It now consists of a main basin, 2,000 fathoms deep at its deepest part, and two subsidiary basins to its north-west, each 1,000 fathoms deep. The main basin is separated from the smaller by the volcanic ridge on which Barren Island is situated. This ridge runs first to the north-east from Little Andaman Island and then north to join the zone of volcanoes in Burma. Southwards, it joins up with the volcano zone of Sumatra. To the west of and close to the Andaman ridge is a subsidiary submarine ridge which, according to Sewell, continues into the Nias-Mentawei ridge south of Sumatra (on the axis of the major negative gravity anomaly strip—Umbgrove, 1949, plate X). Whatever may be the significance of the ridge said to occur west of the Andamans, there is little doubt that the Andaman-Nicobar ridge runs directly into the Nias-Mentawei ridge. There is another submerged ridge (Carpenter's ridge) about 30° west of the Andaman ridge, and separated from it by a gulley called the 'Investigator deep'. According to Tipper, (1911, p. 210) the Andaman ridge is overfolded to the west. The existence of a much wider shelf on the western side of the Andaman ridge than on its eastern is explained by Sewell as due to the progressive eastward shift of the anticlinal axis of the fold, following the suggestion of Brouwer's. The Tenasserim Coast of the Andaman basin, on the other hand, is only moderately faulted. The Shan plateau of Burma which is the northern continuation of Tenasserim, shows a fault scarp on its west along which it is said to be overthrust westwards. It is, therefore, probable that Tenasserim is also similarly uplifted and thrust over to the west.

THE WESTERN COAST AND THE ARABIAN SEA

Submarine contours of the Western Coast of India show that the margin of the continental shelf is remarkably straight from near Cape Comorin to the West of Kathiawar. This lends support to the deduction, from other data, that this coast was faulted down in comparatively recent times. Leaving aside the Gujarat-Narbada Valley zone, which is known to be an ancient zone of weakness, the only marine strata found on this coast are of Lower Miocene age forming a narrow coastal strip in Travancore (Eames, 1950, pp. 236, 239). The Deccan traps near the Bombay coast are over 6,000 ft. thick, becoming gradually thinner eastwards. They show a slight dip towards the sea near Bombay, this being due to the Panvel flexure trending roughly parallel to the coast. It is clear that they could not have stopped abruptly at the coast with such a thickness but must really have extended further west. The western extension has been faulted down into the sea. Between Ratnagiri and north of Bombay there is a series of hot springs along a straight line parallel to the coast, which show that they are located on a line of fracture. This also lends support to the coast being a faulted zone. The age of the fault, as indicated above, is about the Lower Miocene (Oldham 1893, p. 495) or slightly earlier.

The Continental Shelf is limited roughly by the 100-fathom line (Fig. 13). The shelf is generally 25 to 35 miles wide but is widest near about N. Lat. 20°. It slopes gradually over this width and then rapidly down to about 1,000 fathoms. Making an acute angle with the coast and the shelf, is the Laccadive-Maldive ridge which is thought to be the continuation of one of the main Aravalli ridges. It is very likely that the Chagos Archipelago also belongs to that ridge. From the southern end of the Chagos to the northern end of the Laccadives, the distance is 1,500 miles. All these groups of islands rise from platforms which are about 1,200-1,300 fathoms deep. The Chagos Islands are separated from the Maldives by a channel which is about 2 degrees wide and 1,600-1,700 fathoms deep. The Maldive group is separated from the Laccadives by a much narrower channel about 1,200-1,300 fathoms deep. Followed northwards, the Laccadive ridge continues up to Coradiva island, between which and India there is a narrow gap 1,066 fathoms deep. A bank called the 'Adas Bank' was formerly reported to exist in this gap but Sewell (1935) doubts whether it exists. But along the trend of the Laccadive ridge we find two banks on the continental shelf, the southern being the 'Angria Bank' and the northern the 'Direction Bank'. They lead northward, through the Gulf of Cambay, to the Aravalli mountain chains. The idea that these banks represent a continuation of the Aravallis receives indirect support from the fact that a strip of strong positive gravity anomalies runs along it, into the Lacca-

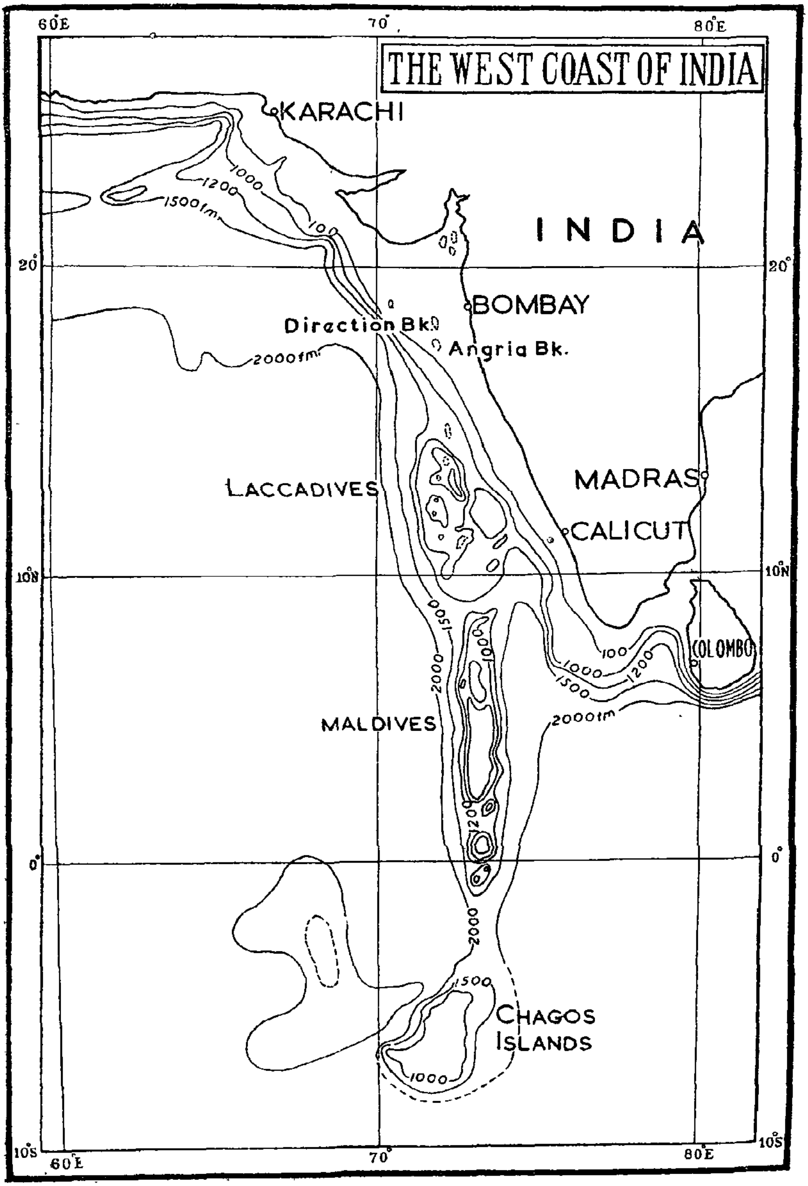


Fig. 13. (After R. B. S. Sewell.)

dives. The Maldives, however, lie in a zone of negative anomalies which at its northern end turns in the direction of Cochin on the west coast of India. It may also be noted that the general alignment of the Maldives is slightly to the east of that of Laccadives, while that of the Chagos is distinctly to the west of the Maldives alignment.

Sewell (1935, p. 426) has called attention to the fact that the Elicalpeni Bank in the south-eastern part of the Laccadive group is separated only by a narrow channel from Malabar and that its position is on the westward continuation of the Eastern Ghats in the Nilgiri region. If there is any truth in this suggestion, it would mean that the Eastern Ghats continued right up to the (supposed) extension of the Aravallis into the Laccadives.

The Kirthar Range, which forms more or less the boundary between Sind and Baluchistan in Pakistan, runs down to Cape Monze near Karachi where it is covered by the sea. The same strata as those near Cape Monze are found in a small island called Churna which lies to the west of Cape Monze (Oldham 1893, p. 312). This feature is seen to continue south-westwards as a well marked submarine ridge (called the Murray Ridge). It rises from the bottom of the sea 1,700-1,800 fathoms below sea level. To its south-east is a gully 2,100 fathoms deep which, when followed in a south-westerly direction, first shows a tendency to shallow to 1,600 fathoms and then resumes its original depth.

About 1° Latitude south of the Murray Ridge is another ridge. At about co-ordinates 10° 20′ N. : 64° 0′ E., it shows a peak which is only 440 fathoms deep, but in general the top of this ridge is about 1,500 fathoms below sea level. It has been traced as far west as 20° N : 61° E. It is not clear whether these two ridges strike into the Oman Coast.

The strip of sea adjoining Mekran (Baluchistan) is streaked with numerous straight parallel ridges which are part of the Zagros mountain system. The sea here gradually deepens to 1,800 fathoms at which depth the bottom is practically flat. The ridges generally rise to heights of 2,500 to 3,000 ft. above the sea floor. Some of the ridges are at a distance of 60 miles from the Mekran Coast.

Since Middle Miocene rocks have been involved in the downfaulting of the Mekran sea, the date of faulting may be late Miocene or Pliocene. It may be that the western coast of India was faulted down in Lower Miocene and the faulting extended into the Mekran region somewhat later. Further extension of this faulting into the Persian Gulf and the Euphrates valley apparently occurred in the Pleistocene.

From the Island of Socotra near the north-eastern tip of Africa, there runs the Carlsberg Ridge system, in a south-easterly and then southerly

direction to Rodrigues (Fig. 14). It is a broad arc convex to the east, rising from the ocean floor at a depth of 2,300 fathoms. The basins on either side are over 2,700 fathoms deep. Concentric to this is another arc, on which are situated the island groups of Seychelles, Saya de Malha,

BATHYMETRIC CHART OF THE INDIAN OCEAN

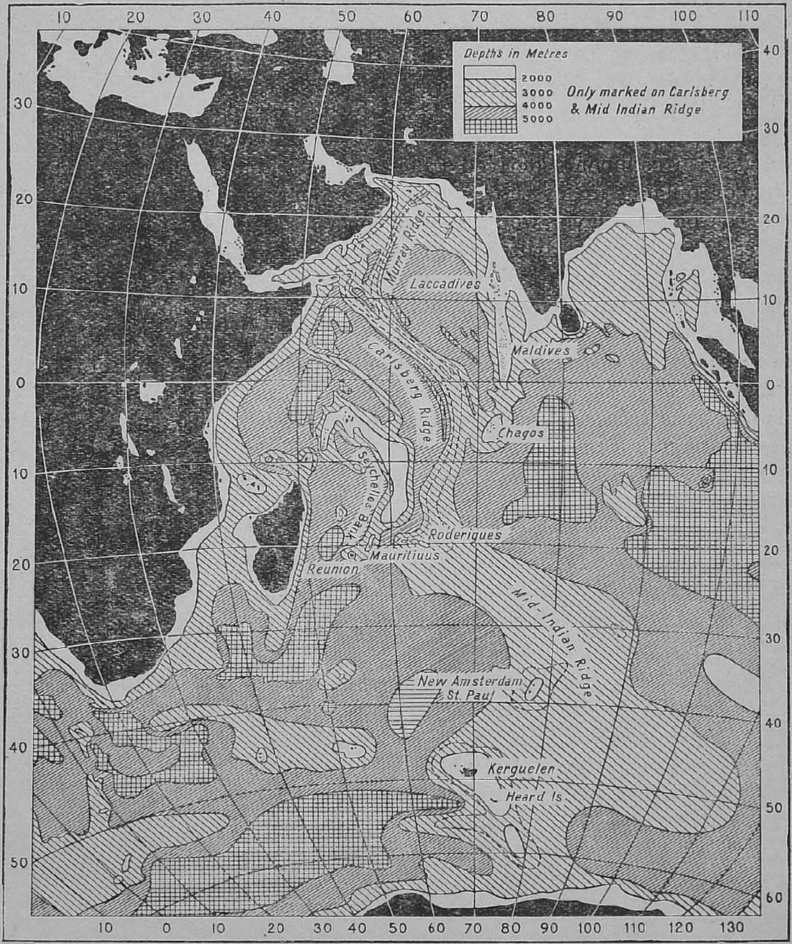


Fig. 14. (After I. D. H. Wiseman and R. B. S. Sewell.)

Nazereth Bank and Mauritius, and on the concave side of which lies Madagascar. Wiseman and Sewell 1937) are of the opinion that the ridge system in the Indian Ocean and th East African rift system

have a considerable degree of similarity and that they form a mirror image of each other along 50°E. meridian. Some of the samples of rock dredged from the surface or sides of the submerged ridges were found to be basalts. This ridge system lies roughly midway between India and Africa and is similar to the Mid-Atlantic ridge between Eur-Africa and the Americas. The origin of the Mid-Atlantic ridge has been explained by different authors in different ways. The Atlantic and Indian Ocean basins are surrounded by markedly fractured coasts and it is therefore reasonable to assume that the ridge systems are due to effects of tension in the respective basins. After Gondwanaland was fractured, the parts drifted apart. The fractured coastal regions would then be loaded with sediments derived from adjacent land, with consequential rising or bulging up of the central strip along which igneous material from the basaltic layer would rise to form a ridge. As the continental masses on either side drifted, adjustment would take place in the mid-ridge by lateral and vertical movements (Du Toit 1937, pp. 217-219, 226-227). The phenomenon would be a sort of the reverse of what happens in a zone of compression connected with a geosyncline, where the sial crust is downfolded, followed by uplift of the sediments in the geosyncline and igneous intrusions, mainly granitic, from below. In this case, the thin sial crust would bulge up and be broken through by basaltic magma from below.

ULTRAMAFIC ROCKS AND OROGENIC BELTS

There are numerous scattered references to occurrences of ultramafic rocks in various parts of India. A general sorting out of these occurrences shows that they fall in one or the other of the known belts of mountain building. When these were plotted on maps the above-mentioned connection was clearly brought out, as will be seen in Figs. 10 and 15 to 17. The writer is obliged to his colleague Mr. N. A. Vemban for carrying out this task of collecting information and plotting the occurrences. An attempt is here made to present only the easily available information, and it is possible that more exhaustive search will reveal other occurrences in these and certain other areas.

The occurrences brought together here include what have been described as peridotites, dunites, saxonites, lherzolites, serpentines and pyroxenites, which in most cases are associated with such alteration products as asbestos, talc, serpentine, and magnesite. Some amphibolites have been included, as it was not clear whether they were derived from pyroxenites or from basaltic rocks.

1. Rajputana

The occurrences in this area mentioned below, are arranged from north to south (Fig. 15).

Numerous lens-like masses and thick sills of amphibolite are found folded in with the Delhi System (Alwar Series) from near Mandarwar (27° 52′ : 76° 36′) to Jhiri (27° 14′ : 76° 16′) and Raialo (27° 5′ : 76° 17′). They seem to be mainly altered basaltic rocks (Heron, 1917).

Steatitic rocks are found in several places in the Biana-Lalsot Hills (Heron, 1917*a*, p. 200) especially near Maroli (26° 46′ : 76° 34′) and Morra (26° 49′ : 76° 52′). The occurrence of Nawai Hill (26° 22′ : 75° 59′) is also of the same nature (Heron, 1922, p. 391). In Central Mewar, B. C. Gupta (1934, p. 124, 156) has recorded the presence of amphibolites in pre-Aravalli and Aravalli rocks near Idra (24° 36′ : 74° 16′), Bhilwara (25° 21′ : 74° 39′) and other places. Talc and chlorite-bearing rocks derived from ultramafics, and serpentines with magnetite are found near Beawar and to the south of Ajmer.

Talc-serpentine rocks occur intermittently along a NNE-SSW zone between Kanhat (24° 23′ : 73° 29′) and Sempala (24° 49′ : 73° 37′) north-east of Udaipur city, according to P. K. Ghosh (1933, p. 449-460). Coulson (1933) has described amphibolites of Delhi and post-Delhi ages from several localities in Sirohi, between Pundwara (28° 48′ : 73° 3′) and Rohera (24° 37′ : 72° 58′). Talc-serpentine-chlorite rocks are developed near Rikhab Deo (24° 5′ : 73° 41′), Kherwara (23° 59′ :

73° 36′) and east of Dungarpur (23° 50′ : 73° 40′), etc. Some of the exposures are large and up to 60 ft. in thickness and their trend is N-S to NNW-SSE (Ghosh, 1933).

Serpentine, chrysotile and steatite occur in several places in Idar according to Middlemiss (1921, pp. 99-109), as for example near Dev Mori (23° 40′ : 73° 28′), Ghanta (23° 36′ : 73° 16′), Kokapar (23° 31′ :

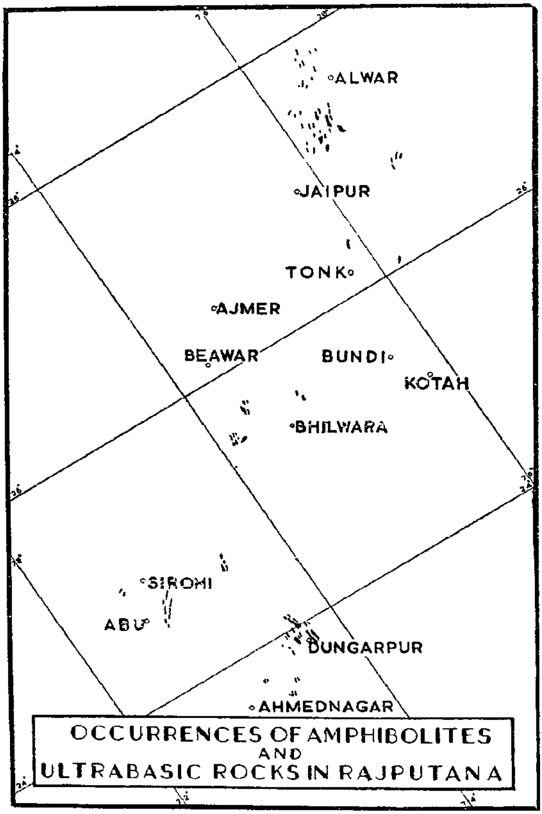


Fig. 15.

73° 28′) and Thurawas (23° 43′ : 73° 16′). Some of these are more than a mile long and up to 300 ft. thick.

Plate 4 shows that all the above occurrences fall in the Aravalli-Delhi belt in which there was orogenic activity in post-Aravalli and post-Delhi times. In Dungarpur and Idar the arrangement of the exposures is N-S or NNW-SSE, following the change of strike of the axis of the folds.

2. Mysore

Coming now to the Mysore region, we find that there is a variety of altered and metamorphosed basic and ultrabasic rocks in all the Dharwarian exposures, and especially in the southern parts of the Shimoga and Chitaldrug belts where the rocks have undergone high grade metamorphism. It is likely that the southern part of the state exposes more deeply eroded sections than the northern part (Fig. 16).

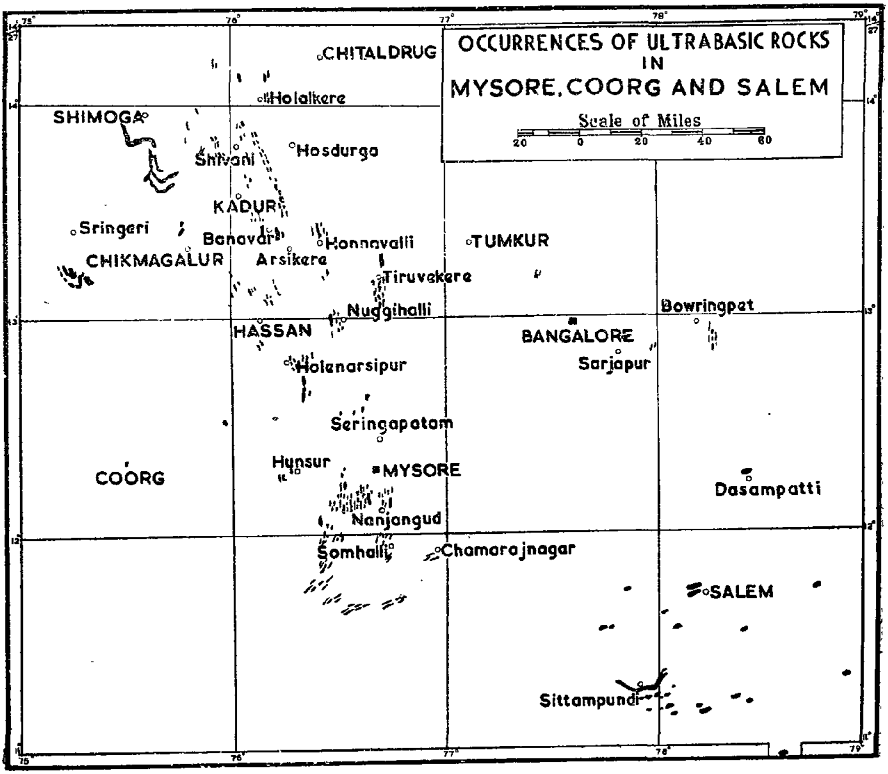


Fig. 16.

Partly altered peridotites and pyroxenites are found in numerous places in the Shimoga and Kadur areas *e.g.* near Jajur (14° 8′ : 76° 1′), Sulikere (14° 9′ : 75° 55′), Holalkere (14 2′ : 76° 13′), Jhandimatti (13° 58′: 75° 51′), Hiriyur (13° 48′ : 75° 46′) Lakkavalli (14° 32′ : 75° 41′) etc. In the Hassan district, serpentine and steatite rocks are associated with amphibolites. There are also pyroxenites, enstatite-tremolite rocks and olivine-bearing rocks near Hassan (13° 0′ : 76° 8′), Holenarsipur (12° 48′ : 76° 17′), Honnavalli (13° 20′ : 76° 27′),

Tiruvekere (13° 10′ : 76° 44′), Nuggihalli (13° 0′: 76° 3′) etc. To the south and south-west of Mysore city, there are numerous bands of hypersthenites associated with charnockites. They are particularly abundant between Mysore city and Nanjangud (12° 7′ : 76° 43′). Peridotitic rocks also occur further south along the same belt near Sargur (12° 0′ : 76° 23′), Hoskote (11° 53′ : 76° 27′) and Rampur (11° 45′ : 76° 27′).

In following the exposures from north to south it is seen that they are confined to the Dharwarian belts and that at the southern end near Mysore the strike becomes N-S, finally assuming further south a NNE-SSW trend, that of the Eastern Ghats here. The details for Mysore have been taken from several papers by E. W. Wetherell, M. K. Slater, P. Sampat Iyengar and B. Jayaram in the Records of the Mysore Geological Department.

3. The Eastern Ghats

As we have already seen, the portion from South Malabar and Nilgiris to Madras (through Coimbatore, Salem and Arcot) is dominated by the Eastern Ghats trend which has a ENE-WSW direction first, and later a NNE to NE direction. Several exposures of dunite and related rocks, mostly converted to magnesite, steatite and asbestos, occur in Salem (Krishnan, 1951). These are also shown in the south-eastern part of the map of the Mysore region (Fig. 16). The ENE trend of the occurrences is very clearly seen in the map. Some of the exposures are fairly large, the 'Chalk Hills' area near Salem being 6 sq. miles in two closely spaced patches. Passing through Sittampundi (11° 15′ : 77° 54′) there are also bands of chromite- and corundum-bearing pyroxenite, amphibolite and anorthosite, shown by a curved branching line in the map.

The Eastern Ghats belt, throughout its length, shows large masses of charnockite which include patches of ultrabasic composition (hypersthenite, enstatitite and pyroxenite) in many places. One such patch near Kondapalle (16° 37′ : 80° 32′) contains small but workable deposits of chromite. Another deposit of chromite occurs at Nausahi (21° 17′: 86° 20′) near Bhadrak in Orissa in peridotitic rock intrusive into ancient gneisses. Charnockitic rocks are, however, by no means confined to this belt, for they are known to occur in the Dharwarians and in the gneisses of southern Mysore, Travancore and Tinnevelly and also in Ceylon, East Africa, Antarctica and Western and Central Australia. But it is not known whether they are all connected with orogenic belts.

4. Satpura Belt

It is only for the Singhbhum area in this belt that data are readily available regarding the occurrence of ultrabasic rocks (Fig. 17). Accord-

ing to J. A. Dunn (1929, p. 96; 1939, p. 50, 143, 236) the ultrabasics were intruded in the main shear zone of the Singhbhum copper belt just after overthrusting took place, but in some cases they have also been affected by folding and dislocation.

To the north of the large area of Dalma volcanics, some distance north of the main shear zone corresponding to the Singhbhum Copper Belt, there is an E-W zone showing sills of pyroxenite in sheared phyllitic

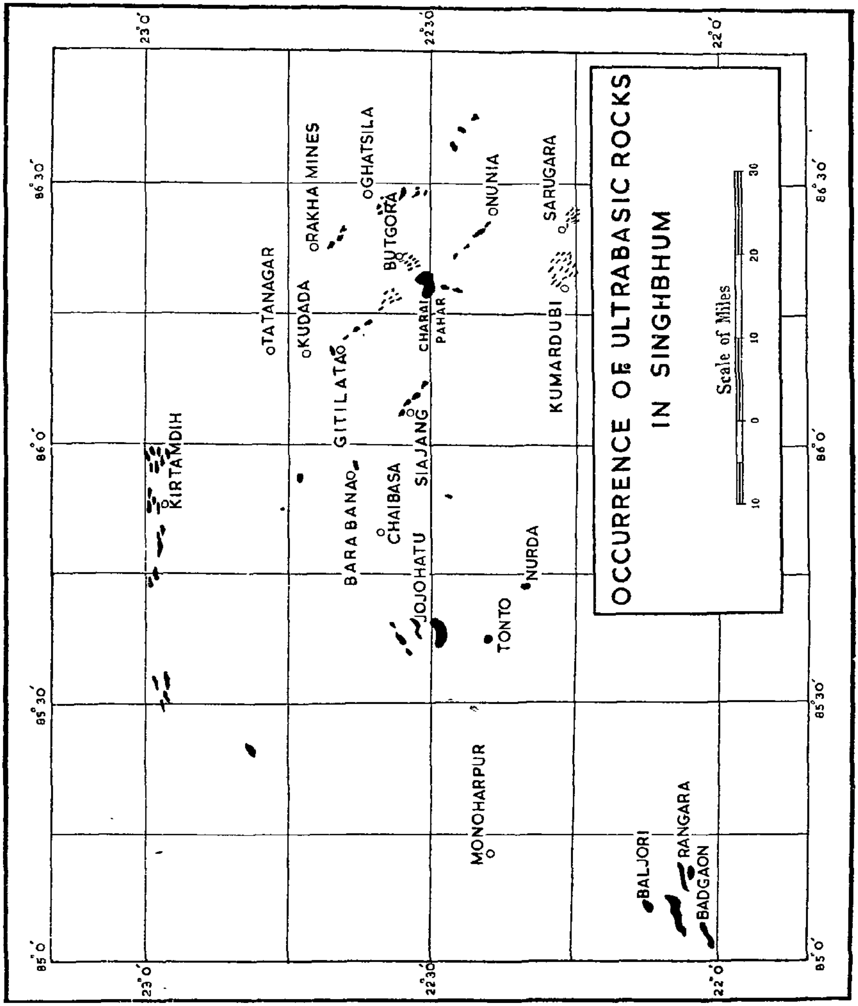


Fig. 17

rocks. These are seen near Kirtamdih (21° 58′ : 85° 51′), Chunadih (21° 59′ : 85° 57′), etc.

To the south and east of Tatanagar, the basic and ultrabasic rocks appear in three or four zones which are more or less parallel to the main shear zone. The easternmost extends from Rakha Mines (22° 40′ : 86° 12′) to Mahulisol (22° 28′ : 86° 34′) and beyond. The occurrence at Kudada (22° 42′ : 86° 12′) may probably belong to this zone. A second zone passes through Gitilata (22° 40′ : 86° 12′), Manpur (22° 36′ : 86° 16′) and Butgora (22° 33′ : 86° 20′). The next includes the large mass of Charai Pahar near Dublabera (22° 29′ : 86° 17′) and a series of small exposures from Lakaidih (22° 26′ : 86° 18′) to Nunia (22° 23′ : 86° 25′). A fourth zone is indicated by occurrences near Bara Bana (22° 27′ : 85° 56′) which possibly connects with Siajang (22° 33′ : 86° 4′). Along the south-eastern extension of this are the large masses of Kumardubi (22° 17′ : 86° 19′) and Sarugara (22° 16′ : 86° 24′) which are basic rocks containing numerous lenses and patches of serpentine and magnetite. The Batgora mass is similar to these.

In addition to the above, there are a few large isolated masses of olivine-bearing rocks (saxonites, lherzolites, pyroxenites, etc.) at the following places (Jones, 1934, p. 217) : Jojohatu (22° 31′ : 85° 38′) comprising three large masses, each several hundred feet thick and containing chromite deposits ; Tonto (22° 23′ : 85° 37′) ; Nurda 22° 20′ : 84° 44′) containing highly serpentinised rocks ; Nangalkata (22° 5′ : 85° 5′), a large laccolith nearly 4 miles long ; Badgaon (22° 2′ : 85° 2′) ; Baljori (22° 5′ : 85° 4′) ; and Rangra (22° 3′ : 85° 9′). These masses are not connected with the shear zones, but appear to be aligned parallel to the Eastern Ghats strike (NNE-SSW) characterising the area in which they occur.

5. The Tertiary Mountain Belt

We have already seen that the orogenic belt of Oman is intimately associated with the Semail igneous suite comprising basic and ultrabasic igneous rocks as well as granites and diorites. The zone of the most intense folding corresponds to the zone of deep sea sediments including radiolarites (Picard, 1937, p. 419 ; Davis, 1950). The Oman ranges very probably extend into the submarine ridge which is a continuation of the Kirthar ranges of Sind.

The Jurassics and later sediments of Cutch are folded along a E.-W. or N. W.-S. E. axis. There are two lines of ‘ trap ’ intrusions, one in Cutch and the other in Patcham and other islands in the Rann. As no modern work has been done on these intrusives it is not known whether they consist entirely of Deccan Trap flows or whether they contain also patches of ultramafic rocks. Wynne (1872) mentions the presence of

coarse augitic rocks in western Cutch which may or may not include pyroxenites and peridotites.

The Baluchistan arc shows sills and intercalations of basic rocks in Upper Cretaceous and Eocene sediments, but the only well-known occurrence of peridotitic rocks seems to be the group near Hindu Bagh ENE of Quetta, which is associated with large chromite deposits which have been worked for about forty years. Similar deposits have come to light recently in the area north of Fort Sandeman along the continuation of the same belt. These are considered to be of Upper Cretaceous age.

Basic and ultrabasic rocks of Cretaceous age are also known in the Burzil-Dras area of Ladakh north of the main Himalayan Range of Kashmir (Wadia, 1937, p. 154). The ultrabasic rocks are serpentinised peridotites, said to contain much associated chromite, extending NW-SE over a length of several miles.

Serpentinised ultrabasic rocks are found in the ' exotic block ' region of Balchdhura and Kiogad in the Kumaon Himalaya. They occupy the Balchdhura heights (18,110 ft.) and some localities along the pass of that name (Heim and Gansser, 1939, pp. 149-164). Similar rocks are known in the region north of Balchdhura, near Jangbwa, south and south-west of Lake Manasarowar, and in the Darchen area south of Mount Kailas. These ophiolitic rocks are considered by Heim and Gansser (1939, pp. 173, 180-189) as younger than the Cretaceous *flysch* sediments with which they are associated. They also point out (pp. 162-163) that the igneous rocks occur with and are intrusive into deep-sea deposits —radiolarites and siliceous sediments—which indicate a possible Upper Cretaceous or early Eocene age. Granitic rocks are intrusive into the Central Himalayas as well as in the Trans-Himalaya range. The intrusion of the ultrabasic rocks should have taken place during the first orogenic upheaval of the Himalaya, *i.e.*, in the Upper Cretaceous (de Terra, 1936, p. 864), more or less contemporaneous with the Oman orogeny.

There is little information on the occurrence of ultrabasic rocks along or near the axis of the main Himalayan range in Nepal and Eastern Himalayas, though it is known to be intruded by large batholithic masses of granite almost throughout its length. More detailed work along this belt in future may bring to light some occurrences.

Numerous occurrences of peridotite and serpentine, some of which are associated with jadeite and others with steatite, are known in the Burmese arc. They are all thought to be of Upper Cretaceous age (Fig. 10).

According to Chhibber (1934*a*, pp. 24, 32) serpentinised peridotite associated with jadeite occurs near Tawmaw (25° 41′ : 96° 15′) ; 10 miles east of Mohnyin (24° 47′ : 96° 22½′) ; between latitudes 25° 28′ and 25° 52′ and longitudes 96° 7′ and 96° 24′ and at a locality 200 miles north of Myitkyina. Several other occurrences are recorded by the same author between North latitudes 25° 20′ and 26° 0′ and East longitudes 96° 5′ and 97° 0′ (*Rec. Geol. Surv. Ind.* *62*, p. 108, 1929; *63*, p. 99, 1930 ; *64*, p. 78, 1931). They are aligned along a N E.-S W. direction.

Peridotite masses, usually altered to serpentine and sometimes associated with steatite, occur 24 miles south-east of Fort Hertz (27° 21′: 97° 24′) as a lense-like outcrop over 5 miles long. About 100 miles south of this there are two groups of outcrops near Myitkyina (25° 23′ : 97° 24′). The eastern group extends from a locality about 4 miles north-east of Myitkyina for a distance of 60 miles to the south ; while the western group which is 15 miles west of this, is 25 miles long, trending in a N. by E. direction.

In Manipur State, near the border of Assam and Burma, there is a large outcrop 25 miles east of Imphal, extending for 40 miles or more in a N. 15° E. direction between latitudes 24° 10′ and 25° 5′. It is several miles wide. Another outcrop is known east of Kohima in the Naga Hills, running for 15 miles in a SSW direction from a locality having the coordinates 25° 50′ N. : 95° E. Numerous small outcrops, some associated with chromite, are known in Thayetmyo, Minbu, Pakokku, Kyaukpyu, Prome, Henzada and Bassein districts of Burma, between 17° 20′ N. and 21° N. and 94° E. and 95° E. (Chhibber 1934*a*, pp. 245-246 ; 1934, pp. 314-317, 470-472). In the southern continuation of this zone, serpentines are found in all the three Andaman Islands and in Teressa, Tilanchong and Kamorta Islands of the Nicobar group (Tipper, 1911, pp. 10, 14 ; Gee 1926, p. 214). Rocks from the Andamans, which were formerly assumed to be tuffs, have recently been found by K. Jacob to be radiolarites (Jacob, *in the press*).

From investigations in various orogenic belts of the world, it has been learnt that during the course of development of a geosyncline, the *sial* layer is weighed down and stretched. Through cracks developed in this layer under tension, magma from the basaltic layer rises up and spreads into and over the sediments, forming intrusions and contemporaneous intercalations with them (Umbgrove, 1947, pp. 77-81). This accounts for the large masses of basic volcanics associated with geosynclinal sedimentation—*e.g.*, in the Dharwarians, Cuddapahs, Iron-ore series, Cretaceous of Baluchistan, etc.

The occurrence of ultrabasic rocks in the intensely deformed and sheared orogenic belts has now been established by Hess (1937*a*), in

particular in the West Indies (1938, pp. 332-333) and in the Island arcs of the Western North Pacific (1948). Thayer and Gould (1947) have also demonst atѐd the association of the shear belts of Cuba with serpentine intrusions.

As a result of the experimental study of the MgO-SiO_2 -HO_2 system Bowen and Tuttle(1949) have come to the conclusion that typical olivine rocks (or olivine—orthopyroxene rocks) are intruded more or lessin a solid condition at a temperature about 1,000°-1,200° C. If the mass encounters water on the way or is attacked by hydrothermal solutions after emplacement, the orthopyroxene is first attacked, giving rise to talc and secondary olivine at about 650° C. With further lowering of the temperature to below 500° C., the minerals will be transformed to serpentine. If olivine is in excess of the correct proportion for complete serpentinisation, brucite may be formed at around 400° C. The iron content of the olivine and pyroxene would give rise to magnetite, which is often seen associated with serpentine. The presence of carbondioxide in the hydrothermal fluids would produce magnesite and free silica at a temperature below 500° C. Thus, depending on the conditions obtaining in the crust during or after the intrusion of the ultrabasic rock, the appropriate mineral or minerals would be formed in the intruded mass.

Mountain building is initiated by tangential compression of the crust. The *sial* layer is sharply downbuckled into a syncline into which ultrabasic rocks are intruded. The tightening of the limbs results in the intense crumpling and squeezing out of the sedimentary material which is then overthrust to either side as exemplified in the Alps and the Himalayas. The sediments of the synclines on either side of the downbuckle would also be stripped and would come up against the overthrusting sediments in consequence of the crust moving inwards and downwards to form the downbuckle. Thus would the Jura type of structures be formed. The different stages are illustrated by Hess (1937*a*, fig. 5) and are shown in Fig. 18.

Experiments performed by Kuenen (1936) with suitable materials show that, as compression is applied to a set of horizontally disposed layers, a series of gentle folds is first formed. With further compression, the main syncline buckles down, later forming a tight fold. Sometimes two adjacent synclines buckle down, forming a double structure. When materials representing light sediments are present over the synclinal stucture they are squeezed out and thrust over the sides. These experiments give considerable support to the ideas put forward by Vening meinesz (1934).

During the first great push downward, the synclinal fold reaches down to a depth of some 60 Km into the peridotite layer some material from which ascends into the axis of the fold either in the centre or on either side of the centre (Hess, 1937*a*, p. 271). This is what has happened in the Himalayas where we get two (including the Darchen zone) zones of ultramafic rocks which are here associated with the exotic blocks. The belt containing these ultramafic rocks is the main negative anomaly strip of the Himalayas. On either side of the downbuckle or

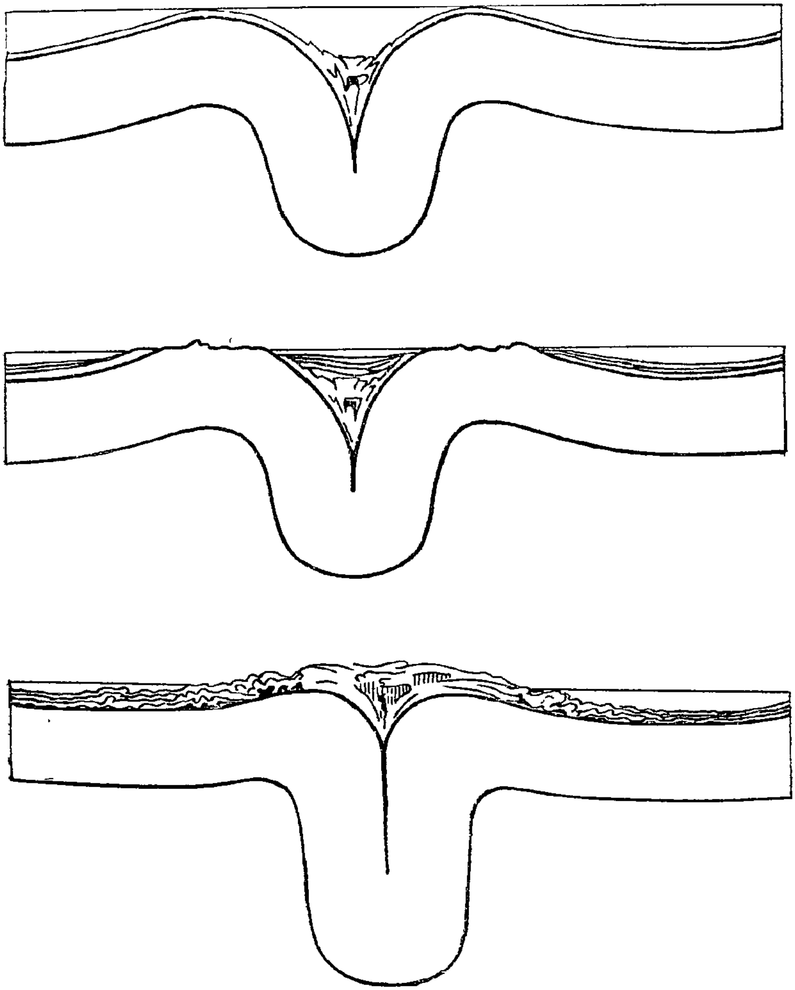


Fig. 18. (After H H. Hess)

tectogene (Hess, 1937, p. 75) there are usually somewhat wider strips of positive anomalies. Further deformation does not produce repeated intrusions of ultramafics as, by that time, the lower part of the tectogene would have softened and sealed off the peridotite magma from below. The later granitic intrusions in the tectogene are due largely to isostatic adjustments which bring up the highly heated lower part of the downfold as intrusions of molten granite and grano-diorite. The period of maximum uplift is therefore later than the period of intense compression, though deformation and thrusting must occur all through.

In the Himalayas the period of down-folding of the crust may be dated as the Upper Cretaceous since the ultramafics (enstatite-peridotites, etc.) of the exotic block regions are intrusive into the Upper *flysch* sediments of that age (Heim and Gansser, 1939, pp. 162, 185). The Tibetan facies of the Upper Cretaceous associated with these intrusions are grey and dark radiolarites which indicate deposition in a deep sea (Heim and Gansser, 1939, pp. 162-164, 173) whose deepening went on while the downfolding was in progress. Little is known about the geology of the country beyond the central Himalayan zone except the observations of Heim and Gansser, but the wide zone containing the two belts of ultramafics and exotic blocks may perhaps be due to the presence of two contiguous downbuckles suggested in Kuenen's experiments. It seems also likely that the zone of granite intrusions of the Trans-Himalayan range north of Mount Kailas may be due to the same cause, *i.e.*, the presence of a second downfold.

As compression increases in the geosyncline, uplift of the sediments will ensue. The lower portion of the down folded *sial* would begin to melt at depth and would be squeezed out to form intrusive masses of granite and granodiorite along the axis of the newly formed mountain. It may sometimes be accompanied by basic rocks, especially in the earlier stages, while the later stages will be marked by assimilation of sediments and migmatisation.

The ultrabasic intrusives in the Archaean mountain belts—Aravalli, Dharwar, Satpura—may be said to be generally of the same age as the period of folding and deformation, though the results of careful and detailed studies are wanting. In the Tertiary mountain belt, the ultrabasics so far known in Baluchistan, in Ladakh and Kumaon, and at various localities in the Burmese arc are assigned an Upper Cretaceous age, which fits in with our deduction of the age of the first diastrophism in the region.

SEISMIC PHENOMENA

Seismic phenomena in India, their distribution and significance in relation to structure have been dealt with in a general way by T. Oldham (1883), Count Montessus de Ballore (1904) and West (1937), while individual earthquakes of importance during the last 50 years or so have been described by various geologists and meteorologists.

The Peninsular part of India is immune to all but very minor shocks which are occasionally recorded. These may be due to local disturbances produced along the fractured western coast of India or to the sedimentary loads deposited in the sea by the larger rivers. The sympathetic shock reported at Cochin at the time of the Bihar earthquake of January 15th, 1934, is apparently of such a nature.

Earthquakes of considerable intensity occur all along the fold belt of the Baluchistan, Himalayan and Burmese arcs. Occasionally also they have occurred in the floor of the Gangetic depression and in and around the fractured horst of the Assam plateau. The Bihar earthquake of 1934 is attributed to movement in the fractured and alluvium-filled floor of the fore-deep (Dunn *et. al.* 1939), while the Dhubri earthquake of 1931 was caused by adjustment along the faulted north-western margin of the Assam plateau (Gee, 1934). The Cutch earthquake of 1819 (R. D. Oldham, 1926) may be attributed to a fault at the junction of the folded sedimentaries of Cutch and the Archaean rocks lying to their north, or to a zone parallel to it within the folded rocks themselves.

In the Assam-Burma region, seismic phenomena may be manifested along one of the overthrusts of the Burmese arc ; along the fault zone which separates the above mountain belt from the Tertiaries to its east ; or along the fault zone which separates the Tertiaries from the ancient sedimentaries of the Shan Plateau.

Plate 2, showing the epicentres of earthquakes recorded by seismological observatories in recent years, has been prepared from data contained in the recent work of Gutenberg and Richter (1949), supplemented by those from papers by Pendse (1948) and Sohoni (1950) of the India Meteorological Department. Epicentres of shocks originating at shallow depths (normal) are shown by dots while those originating at greater depths are marked by crosses on this map. The epicentres show a wide distribution in the Tertiary orogenic belt of Burma, the Himalayas, Baluchistan and Iran. There is a clear indication of a seismic belt in the Carlsberg Ridge system in the Arabian Sea. A very conspicuous clustering of epicentres of shocks of both shallow and intermediate focal depth occurs in the Pamir—Hindukush region where,

apparently, active readjustments are still taking place as a result of the late Tertiary Himạlayan movements. Clustering on a limited scale is also indicated in the region of Quetta in Baluchistan. These may perhaps be attributed to the disturbances caused by the wedge-like projections of the Indian shield which are directed towards these regions and have produced high compression in the crust as evidenced by the remarkable bends of the outcrops of strata and of the orographic features.

GEODETIC EVIDENCE

We have already seen that the Himalayas are typical folded mountains which resulted from the compression of a geosynclinal trough. The core of the mountain belt exhibits large masses of granitic intrusives as well as some basic and ultrabasic rocks. On the convex side of the mountains, *i.e.*, on the side of India, there is a trough filled with Pleistocene and Recent alluvium.

Gravity observations in India show that there are several zones and areas of positive or negative anomalies, after corrections have been made for topography and isostasy (Plate 3). It is now generally accepted that irregularities of surface topography are more or less compensated for by excess or deficiency of matter, as the case may be, in the lower crustal layers and that at some depth, of the order of 60 miles, complete compensation or equilibrium is attained. In spite of nature's effort at isostatic compensation, there are many regions where notable anomalies exist, particularly in folded mountains, in ' island arcs ' and in ocean deeps near them, whatever hypothesis of compensation is advocated and applied. Such regions of marked anomalies always indicate geological instability, foreshadowing further changes.

From an examination of the plumb-line deflections in India, Sidney Burrard of the Survey of India came to the conclusion that the effect of the Himalayas was modified by the presence of heavy or light masses of sub-crustal rocks in certain regions. He thus deduced the presence of a sub-surface ridge of heavy rocks running across India roughly east to west through the region of Jubbulpore, and a parallel zone of light rocks passing through Belgaum and Nellore in South India. The former is often referred to by the Survey of India as ' Burrard's Hidden Range ' on the supposition that the heavier layers of the earth's crust (*Sima* and peridotite layers) have here come nearer the surface and formed a sort of anticlinal ridge. The corresponding zone of lighter rocks in South India (Nellore-Belgaum) is referred to as ' Burrard's Hidden Trough ', expressing the idea that the lower layers of the crust have been depressed into a synclinal trough which is occupied therefore by a larger thickness of the light rocks of the upper crust. North of the ' Hidden Range ' is another parallel zone, passing through the valley of the Indus and Brahmaputra rivers and Manasarowar Lake, beyond the main Himalayan range, which is also a ' trough ', (Glennie, 1932, Chart I).

According to Glennie (1932, p. 3), the sedimentary trough of the Himalayas is deepest along the Indus-Brahmaputra valleys north of the main Himalayan range. This trough line follows the general curvature of the Himalayas while the ' Hidden Range ' and the ' Hidden

Trough' passing through Central and South India are progressively less curved. It is rather interesting that these three major lines are separated from each other by about 8 to 8½ degrees of latitude. If the Himalayan orogenesis is attributable to the north-eastward (or NNE)

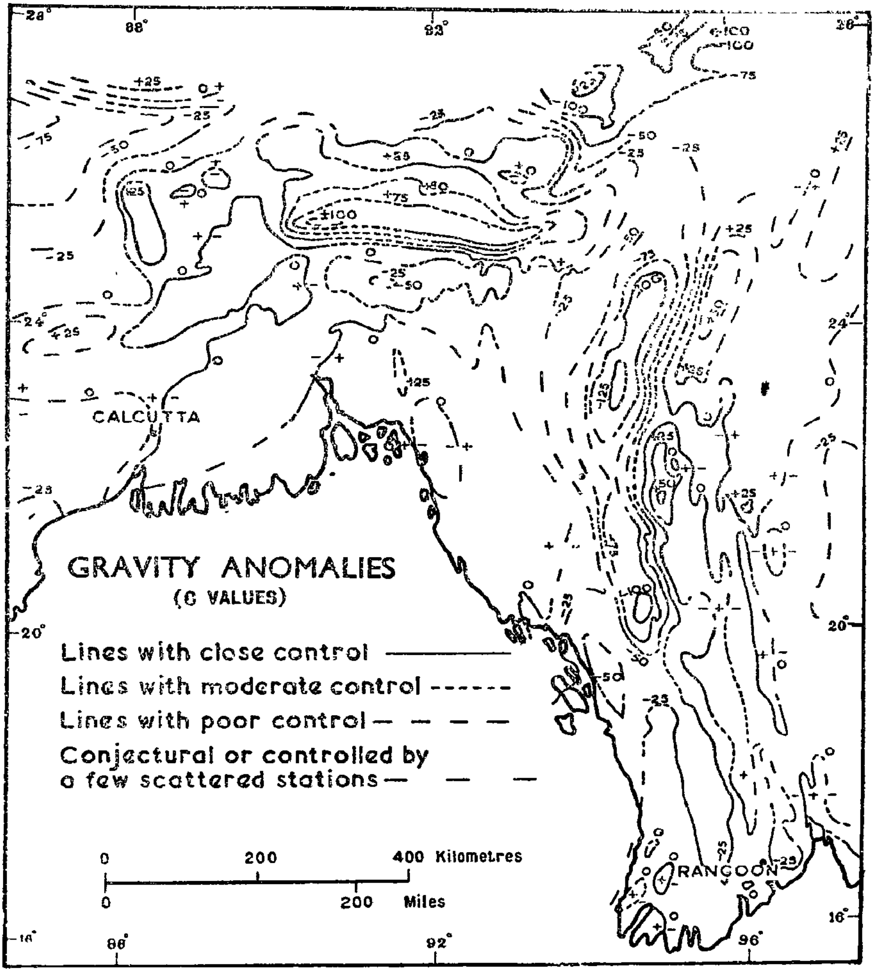


Fig. 19.—Gravity Anomalies (C Values) in Assam and Burma.
(After P. Evans and W. Crompton)
(*By courtesy of the Geological Society of London*)

drifting of India, the arrangement of this 'ridge and 'trough' system may also be due to the same cause.

The alluvium-filled trough through which the Ganges flows in the North Indian plains is of the nature of a foredeep, a slight buckling

down of the upper crust in front of the convex mountain arc. The Brahmaputra Valley in Assam is a continuation of the same feature. It was first thought that the Gangetic Valley was a V-shaped depression filled with alluvium having a thickness of perhaps up to 50,000 ft. (Burrard, 1912). Such a thickness has since been shown to be improbable by Jeffreys (1929, p. 201). Some geophysical measurements made in Bihar after the 1934 earthquake show that the alluvium is about 6,000 ft. thick there. It is not known whether this is an average thickness or the maximum. In any case, an upper limit of perhaps 10,000 ft. for the thickness of the alluvium is now thought reasonable.

To the north of the Himalayan region is a belt of negative anomalies passing through the Pamirs and Ferghana Valley where the free-air anomalies are said to attain magnitudes of about minus 150 milligals. From the isostatic anomalies for this region, worked out by using different hypotheses, it has been deduced that the crust here (*i.e.*, the *sial*) may be as much as 22 to 35 km. thick (Gulatee, 1940, p. 55). Mushketov (1936) has suggested that this region is one of recent uplift in addition to having been affected by the Himalayan orogeny.

Vening-Meinesz explains the formation of mountain chains as due to a downward buckling of the *sial* deep into the *sima*. During the process, the down-buckle reaches into the peridotite layer, the material from which rises up into the axial part of the fold. Later basic and acid magmas are injected profusely into the same region and large intrusives of granite result from the remelting of the *sial* crust which has been depressed. It is the deep down-buckling of the *sial* which gives rise to negat ve anomalies along the zones of mountain building. The down-buckle causes the displaced basic magma of the basaltic layer to rise on either side of it, producing somewhat broader zones of positive anomalies ; but the positive anomalies are, as a rule, smaller in magnitude than the negative anomalies of the down-buckled zone.

In a subsequent paper, Glennie (1940) has explained the various regional anomalies as due to local upwarps or down-warps of the subcrustal heavy layers. In some cases they have no direct connection with the surface geology. For example, though the Deccan Traps occupy a large area, the anomalies are by no means unifo m over that area and are indeed erratic. A belt of high positive anomalies runs through the Gulf of Cambay and along the Bombay coast, which may be attributed to basalt having come up comparatively close to the surface. A similar upwarp of the basaltic layer may also be present along the western end of the Satpuras by the side of the Narbada river.

There are, however, a few interesting coincidences between the crusta warp map and the surface geology. For instance, the highly compressed, granite-injected Archaean ranges of the Aravallis, Dharwars

and Satpuras, the Assam Plateau and Shan Plateau are regions of positive anomaly, while the Cuddapah basin of Madras, Chattisgarh and Gwalior which contain thick unmetamorphosed sediments are zones of negative anomaly.

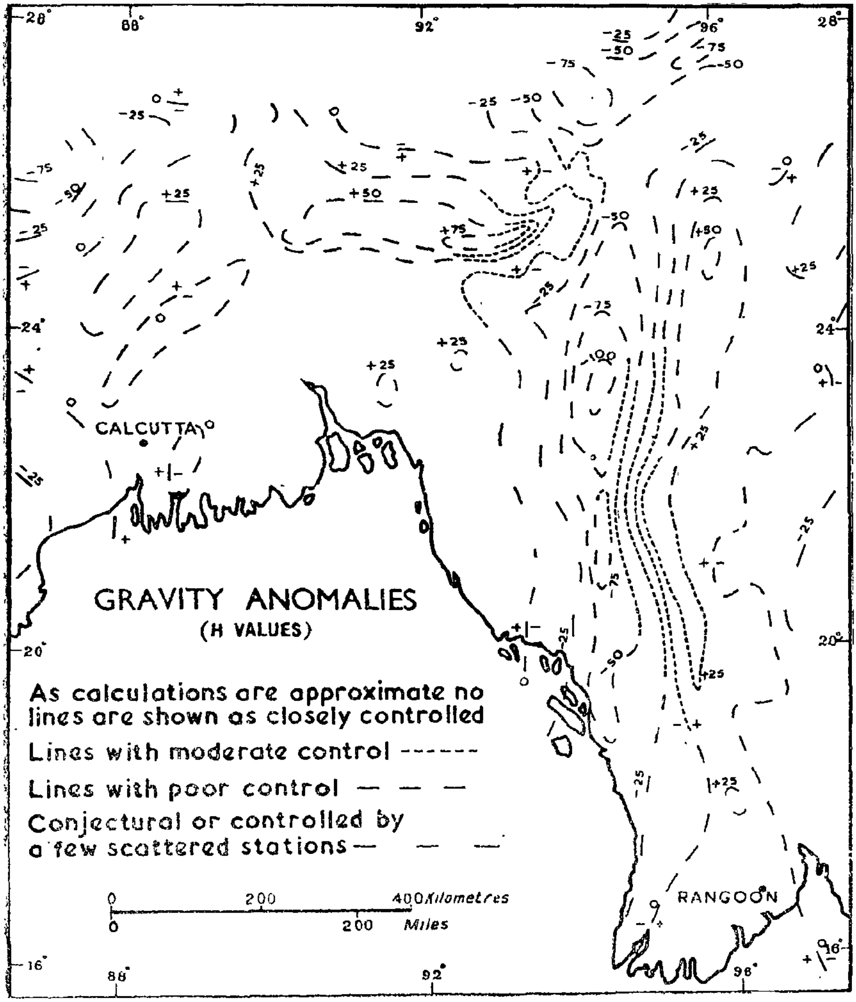


Fig. 20.—Gravity Anomalies (H. Values) in Assam and Burma.
(After P. Evans and W. Crompton)
(By Courtesy of the Geological Society of London)

In a recent paper, Evans and Crompton (1946) have given the results of the gravity survey of the Assam-Burma region in which gravity

observations were recorded at about 6,000 stations. In addition to the conventional isostastic anomalies, they have also computed the anomalies after carrying out corrections for local geology.' The geological corrections have been carried down to a depth of 11·5 kms., as data about the formations and their specific gravities were available from extensive records of bore-holes put down for petroleum by the Burmah Oil Company (Figs. 19 and 20 which are reproduced here with the kind permission of the Geological Society of London).

There is a marked zone of negative anomaly along the eastern flank of the Burmese (Assam-Arakan) arc continuing apparently into Andaman-Nicobar Islands. This is the zone of maximum uplift during the Tertiary mountain building movements, containing great thickness of Tertiary sediments.

There is a zone of high positive anomalies along the volcano belt of Burma, containing the volcanos Taungthonion, Wun-tho, Monywa, Popa, Barren Island, etc., continuing into the volcano zone of Sumatra and Java. The Shan Plateau shows only weak positive anomalies as it is a long time since it experienced mountain building activity.

The Assam plateau is a region of high positive anomalies. There is little doubt that it is continuous with the Bihar Archaeans. The Upper Assam Valley as well as the Ganges Valley in Bihar are regions of negative anomaly as they are troughs filled with thick recent sediments.

It is a matter of interest that the Red Sea is an area of positive anomalies in contrast with the East African Rift Valleys which show negative values. Though the Red Sea is generally considered to be part of the Rift System, the rift here is of large dimensions and partakes of the character of the much larger rifts of the Atlantic and Indian Oceans. The Red Sea bottom, it would appear, is largely denuded of its *sial* crust and the basaltic sub-stratum must be fairly close to the sea bottom. Bullard (1936), who investigated the gravity conditions of the East African Rift areas, is of the opinion that these rifts were not tension fractures but were really formed by compression and faulting.

Vening-Meinesz found that the anomalies over large parts of the Atlantic Ocean are positive, of the order of +36 milligals (Hayford values). Since both the Atlantic and Indian Oceans are thought to have been formed by rifting and by the drift of the sides apart, they should show closely similar characters, including gravity anomalies. The Mid-Atlantic and Mid-Indian Ocean ridges should also show similarity to each other as they have evidently been formed as a result of the same cause and in an identical manner.

7 JAN 1954

SUMMARY AND CONCLUSIONS

We have seen that India, excluding the mountain belts surrounding it in the north, is an ancient stable mass or 'shield' which has suffered little folding since the Pre-Cambrian. The ancient grain is along four major regional trends :—

(i) The Aravalli trend in Rajputana (NE.- SW.) spreads out in Gujarat, one branch going into the Laccadives through the Gulf of Cambay and the other into Mysore and Hyderabad.

(ii) The Dharwarian trend (NNW-SSE) of Mysore and Hyderabad is most probably the southerly continuation of the Aravalli trend. The trend in the southernmost districts Madura and Tinnevelly), in north-eastern Hyderabad and in the hinterland north-west of the Eastern Ghats in Orissa and parts of the Central Provinces, which is NW-SE in general, may be the extension of the same Dharwarian influence.

(iii) The Eastern Ghats trend is characteristically NE-SW all along the Eastern Ghats from north-east Orissa to the Kistna river. The northern part occupies a broad area, in the western half of which the trend is NNW-SSE as seen typically in the Iron-ore Series and iron-ore ranges of Keonjhar-Bonai-Singhbhum. In the Nellore region bordering the Cuddapah Basin, it shows a sigmoidal curvature with a slight convexity to the east and finally veers to the SW near Madras and to the ENE-WSW in Coimbatore and the Nilgiris. It is thought that the same trend becomes E-W in South Malabar.

It will be noticed that this belt cuts across, and is superposed on, the Dharwarian trend, separating the Mysore from the Madura-Tinnevelly areas.

(iv) The Satpura trend (ENE-WSW) characterises the rocks of Narbada-Son drainage region continuing into northern Bihar and the western part of the Assam plateau. A southerly branch is seen in Nagpur -Chindwara-Balaghat region of the Central Provinces, and Gangpur and Singhbhum further east. The area between the two is occupied by granites and gneisses with the same general trend. At its western end it appears to merge into the Aravalli trend where the latter splays out widely. In Bhandara in the Central Provinces, and in Southern Gangpur in Orissa, there are two small areas where a triangular pattern due to the coming together of these trends is seen.

Regarding the relative ages of the orogenies which have produced the above regional strikes, it would appear that the Aravalli and Dharwar are identical. The Eastern Ghats trend which is superposed on (and flows around) the Dharwarian seems to be younger. There are indications in Gangpur (Orissa) that the Satpura trend is younger than the one whose vestiges are found there, presumably the Eastern Ghats trend. Holmes has come to the same conclusion from structural considerations as well as from data on the age of radioactive minerals found in pegmatites traversing these belts. But, as Fermor has pointed out, this does not settle the ages of the Archaean and Pre-Cambrian formations of the different regions.

On the Archaean basement were laid down thick deposits of Algonkian age (Cuddapah and Vindhyan), remnants of which are found in the Cuddapah basin of Madras, the Chattisgarh-Mahanadi area of the Central Provinces and Orissa, and the great Vindhyan basin of upper India. The Cuddapahs are more disturbed than the Vindhyans which have generally suffered little or no folding or metamorphism. The eastern margins of the Cuddapah and Chattisgarh basins and the southern margin of the great Vindhyan basin have suffered some folding and disburbance from forces which followed the older trends of the particular areas. The western margin of the great Vindhyan basin is marked by a fault of great magnitude along which the Aravallis and Delhis have been uplifted and thrust against the Vindhyans, probably in the Mesozoic.

The Gondwanas were ushered in by a great ice-age. Over the initial tillites were laid down fluviatile and lacustrine strata containing the *Glossopteris* flora and coal seams in the Permo-Carboniferous and Permian. This was followed by semi-arid conditions characterised by red sandstones and sandy clays with amphibian and reptilian remains. Again followed a more moist era in the Upper Gondwana (Jurassic), characterised also largely by fluviatile and lacustrine sediments in which the flora is of the *Thinnfeldia-Ptilophyllum* group. Marine incursions appeared on the eastern coast showing that this coast was already taking shape in the Jurassic. The Rajmahal area appears to have undergone some slight folding in Upper Triassic times, followed by eruptions of basic lava in the Middle Jurassic. The marine deposits on the eastern coast are apparently Upper Jurassic to Neocomian. Then occurred an uplift and erosion, as a post-Jurassic peneplane is recognised.

To the north and northeast of India, there was a sea from the Cambrian onwards. The Cambrian sea stretched into Indo-China and Southwest China and into Australia. During the Ordovician and Silurian, this sea connected with the American area probably through Southern Europe, while the Burma-China sea connected with the Baltic. In the Middle Devonian, the barrier separating the above mentioned two seas seems to have been removed, at least partially. In parts of the Hima-

layan area there seems to have been marine regression and shallowing of the basin in the Devonian.

The Middle to Upper Carboniferous Hercynian revolution, which brought into existence several mountain ranges in Central and Northern Asia, also saw the establishment of a great latitudinal geosyncline (the Tethys) stretching from the Alps through Iran, Baluchistan. Himalaya, Burmese and Banda arcs to New Guinea and also into Western Australia. At the same time, Gondwana sedimentation was initiated in the Southern Continent (Gondwanaland). An arm of the sea, probably very narrow, seems to have extended in Permian times to Rewa in Central India from Southern Rajputana through Cutch and the Narbada Valley, but the Tasman geosyncline of East Australia was cut off from the Tethys in Lower Permian. Sedimentation continued in the Tethyan basin right through the Mesozoic, till it was broken up by the Himalayan orogeny in the Upper Cretaceous and Tertiary.

A rift, which later developed into the Indian Ocean, was formed between Africa and India-Madagascar in the Permian. This was gradually widened subsequently. This rift extended southward into Patagonia in the Cretaceous. India began to drift from Madagascar and Africa perhaps also in the Cretaceous.

The Red Sea rift appears to have developed in the Upper Triassic and Arabia also drifted north-east, with probably an anti-clockwise twist in the Cretaceous.

The Callovian unconformity (regressions) in the Himalayan area is more or less coincident with the marine transgression over Southern Rajputana and Cutch. To the south of Cutch and Kathiawar there must have been land, *i.e.*, a westward extension of the Peninsula which seems to have been faulted down in the Miocene.

The Middle Cretaceous was a period of intense orogeny in Oman. As a result, the sediments of the Oman basin were pushed back to the north-east and uplifted into mountain ranges, accompanied by eruptions of lavas and intrusive granites and serpentines. It would appear that, because of the northerly drift of India at the same time, a milder orogeny took place in the Baluchistan arc accompanied by volcanics and intrusive serpentine, assigned to the Upper Cretaceous. There is evidence of a shallowing of the margins of, and of the intrusion of ultrabasic rocks into, the Himalayan area of the Tethys at about this time. The Jurassics of Cutch were folded and the folding movements apparently affected the Gondwana sediments of the Narbada-Son Valleys. The Great Boundary Fault of Rajputana, along which the Aravalli belt was thrust up against the Vindhyans on its east, may also have been formed at this time (or earlier), as it is a compression

phenomenon, and is pre-Deccan trap in age. That is to say, the compressive effects on the Baluchistan arc may have been felt in the Aravalli belt which was overthrust in a south-easterly direction on the Upper Vindhyans. The Burmese arc, continuing through the Nias-Mentawai ridge into the Banda arc was folded in Laramide times, a little later than the period of folding of the Oman and Baluchistan areas. In this long belt, the Laramide orogeny initiated by the northward drift of India would appear to have been helped by a similar drift on the part of Australia and New Guinea at the other end. At the same time, the stable mass of Cathaysia and Indo-China were probably gradually spreading out to the east and south, contributing thereby to the formation of island arcs.

Then followed a period of tension during which the Deccan Traps were erupted at the end of the Cretaceous and in Lower Eocene. Vast amounts of lava have risen through the weak zones of Cutch, Kathiawar, the Narbada Valley and alongside the Aravalli axis parallel to the Bombay coast as well as through numerous fissures elsewhere. The later dyke swarms are largely confined to the above mentioned zones in western India and may have been intruded late in the Eocene. Faulting occurred later, as a result of which segments of the crust in these areas have foundered differentially.

The Gondwana trough faults may have been formed any time after the Jurassic, as precise data on the age of the trough-faults are lacking.

The great Cenomanian transgression invaded parts of South India, Assam-Burma, West Australia, Madagascar and East Africa. From this time onward, these areas show an Indo-Pacific fauna while Arabia, Baluchistan and the Narbada Valley were invaded by a gradually increasing Mediterranean element which came through Syria and mingled to some extent with the Indo-Pacific fauna.

The Himalayas were formed during a series of great orogenic movements separated by periods of comparative quiescence. The initiation of deformation seems to have taken place in Upper Cretaceous. Heim and Gansser (1939, 162-163, 173) state that the ophiolitic rocks are intrusive into the Upper Flysch of Upper Cretaceous age and are associated with grey and dark radiolarites of deep sea deposition belonging to the Tibetan zone. The deep sea deposits must represent the period when the downbuckling was taking place. The exact dating of the ultramafic intrusions must await further work in the Central Himalayas. The later movements took place in uppermost Eocene, in Middle Miocene, at the end of Pliocene, in Pleistocene and even in Sub-Recent times. The Mid-Miocene orogeny is considered to be the most violent of all when great masses of granite were intruded into the axial region of the main Himalayas. The succession of mighty ranges

one behind the other, the great magnitude of the thrust-sheets (nappes) and the violent disarray of the rocks, all point to a tremendous shortening of the crust in a direction at right angles to the Himalayan arc, amounting to many hundreds of miles. In the Banda arc there were movements in (?) Oligocene, Mid-Miocene (e4), Upper Miocene (f2) and early Pleistocene, the Upper Miocene one being the most intense. From the data on palaeogeography and diastrophism contained in Umbgrove's recent publication (1949) it is clear that it is the outer arc of the East Indies (the belt of negative anomalies) that corresponds to the axis of the Burma-Andaman arc.

Within India, the Assam wedge lying in the angle formed between the Himalayan arc on the north and the Burma arc on the east and south-east, was overthrust from both the sides. Faults developed around the Assam Plateau and it was uplifted in or about the Middle Miocene.

There was a marine transgression of Middle Miocene age along the coasts and this separated Ceylon from the mainland by a very shallow sea. At the same time a strip of unknown extent which certainly included the southern part of the Aravalli belt, was faulted down along the West Coast, giving the final outline to that coast. The Mekran Coast was faulted down in the Pliocene, for we find Upper Miocene sediments are involved in it. The Oman and South Arabian coasts were faulted in post-Eocene times, perhaps in the Oligocene or Miocene.

The intense mountain building movements produced a depression or 'fore-deep' in front of the convex side of the Himalayan arc because of the bending down of the northern edge of India which came into opposition with the Central Asian mass. This fore-deep is not a continuous depression throughout the length of the Himalayas, but consists of three strips on the same alignment, separated from each other by transverse ridge-like structures west of Delhi and in the region east of Cooch-Behar. The troughs correspond more or less to a strip of negative gravity anomalies. There is another negative strip along the Indus-Brahmaputra Valleys in Tibet north of the main Himalayan range.

The last-mentioned negative strip is parallel to Burrard's 'Hidden Range' and to the 'Hidden Trough'. They are separated from each other by a distance of about 8° to 8½° of latitude. As the latter two features cut across a variety of geological formations, they are attributable to the depression or elevation of the sub-crustal layers. The parallelism of these to the Himalayan arc, and the correspondence of the northern negative strip with the deep part of the Tethyan basin, indicate that they all resulted from a single cause, *viz.*, the Himalayan orogeny and the northward drift of India. The Hidden Range and Trough

suggest the crest and trough of a sub-crustal wave generated during the drift which has not yet had time to be smoothed out.

The fore-deep, or at least the northern part of it, is doubtless underlain by Tertiary and older rocks which dip down into it from the Himalayas. Similarly, the rocks on the Peninsular side may also be expected to continue into it from the south. The bottom of the trough is likely to contain fractures which may have been formed when it was bent down. Such a fracture zone, being a zone of weakness, is thought to be adequate to provide a locus for earthquake shocks. Indeed, the Bihar earthquake of 1934 has been attributed to movement in such a zone underlying the Ganges Valley.

The two extremities of the Himalayas are marked by wedges of the Peninsula jutting out to the north-west and north-east respectively. The influence of these wedges is felt as far north as the Pamir region in the north-west and S. W. China in the north-east, for the mountain ranges there show conspicuous sharp bends towards the appropriate direction in these places.

If we examine a geological map of the Tethyan geosynclinal belt from Iraq through Iran, Baluchistan, Himalaya and Burma to the Indonesian archipelago, we see that the general direction of the Iraq-Persian Gulf region points directly towards Sumatra and is continued by the Indonesian arc. But it is violently distorted and pushed to the north by the foreign mass of India just as Southern Iran is distorted by the Arabian mass. It seems, therefore, not unreasonable to assume that the line connecting Iraq and Indonesian arcs was not far from the original position of the southern limit of the Tethyan geosyncline and that the distortion of the line gives us roughly a measure of the drift of India to the north (or N. N. E.) and of the shortening of the crust by the compression involved in Himalayan orogeny. The distance between the postulated original position of the southern limit of the Tethyan geosyncline and the southern limit of the Himalayan arc is about 13 to 14 degrees of latitude or some 800 miles.

Heim and Gansser (1939, p. 226) have made an estimate of the original width of the sedimentary zones of the Himalayas and deduced the shortening of the zones as a result of mountain building.

The zones are :—

1. The old Gondwana continent buried under the Gangetic alluvium.
2. The autochthonous region of the Simla Slates and the Eocene Subathus, partly covered by the Siwaliks; original width perhaps 100 km.

3. The exterior sedimentary zone of the Lesser Himalaya with the Mandhali-Nagthat-Blaini-Krol-Tal succession; original width perhaps 20 km. or more.
4. The interior sedimentary zone of the Lesser Himalaya with unfossiliferous limestones, dolomites, shales and quartzites of the Tejam-Pipalkoti zone (possibly the equivalents of Krol-Tal); this underlies the crystalline sheet and is thrust over the autochthonous zone; original width perhaps 100 km. or more.
5. The missing normal sedimentary cover of the crystallines of the Lesser Himalaya which must have contained the passage from the unfossiliferous rocks of the Gondwana border to the fossiliferous Tethyan facies; this must have had a width of at least 120-150 km.
6. The Himalayan Tethyan zone 110-130 km. wide; northern Himalayan ranges 20 km. wide.
7. The zone of Chilamkurkur considered as the normal northern extension of zone No. 6.
8. The supposed passage zone to the Tibetan facies (Exotic blocks etc.) which is now entirely unknown.
9. The Tibetan facies (Kiogad and Exotic facies) representing a deep-sea facies—width unknown.
10. Zone of the Trans-Himalaya—width unknown.

The estimated width from the northern border of the Indian plains to the Exotic zone is thus, according to these authors, 100+20+100+120+100+20=460 km. as a minimum. The actual width of these zones at present is about 160 to 170 km., so that the difference between the two, about 300 km., would represent the shortening of the crust. However, it should be pointed out that this estimate may be out by 100 to 200 per cent.

In making an estimate of the shortening of the crust in the Indo-Tibetan region, it should be realised that the Tertiary orogeny affected the whole region from the northern border of the Indian Peninsula to the Kun Lun ranges in Tibet and formed a whole series of mountain ranges—the Himalaya, Ladakh-Kailas, Trans-Himalaya, Karakorum and Kun Lun. According to Mushketov (*see* Gregory, 1929, p. 178) the Alpine-Himalayan mountain building movements affected all the region up to the Trans-Alai where the early Tertiary thrusts are directed towards the north. The same author states (1936, pp. 885-894) that the Alpine thrusts in the Kun Lun—Karakorum region are superposed on the older (Variscan) folds. 'Vast portions of the Palaeozoic

structures (Kunlun, Alai, Tienshan) were welded to the Tethyan folds, with which they form a large unit ', according to De Terra (1936, p. 869). Marine conditions in the Karakorum and Kun Lun regions gave place to estuarine and land conditions after the late Cretaceous upheaval of the Tethyan basin ; in fact, De Terra calls the first Himalayan orogenic upheaval as the *Karakorum phase* (De Terra, 1936, p. 859). The vastness of the region affected and the succession of the mountain ranges formed by the Himalayan revolution would support the deduction indicated above (about 800 miles) about the magnitude of the crustal shortening.

In an indirect way, we may gauge the magnitude of the compression from a look at the geological map of Baluchistan. The Mesozoic and Tertiary succession (itself subjected to broad folding) seen between latitude 30° N. and the submarine continuation of the Kirthar range off the Mekran coast at about latitude 23° N, is gathered up and tightly compressed into less than one-fourth of its width in the Sibi-Quetta region by a projecting wedge of the Peninsula. The compression of the Tethyan basin between the masses of India and Central Asia should be at least of the same order.

The intensity of the compression of the Tethyan geosyncline has found expression in the great recumbent folds and thrust sheets seen in the Himalayan, region. The lateral arcs (the Baluchistan and Burmese arcs) were formed at the same time by the sediments at the sides being comparatively mildly thrust over the north-eastern and north-western borders of India. Though the folding in the lateral arcs is often of considerable intensity it is not so violent as in the Himalayan region where the sediments have been piled up to form the highest mountain ranges in the world. The violence of the movements has been responsible for the almost complete absence of unbroken structures suitable for accumulation of petroleum in the Himalayan region. The Baluchistan region has suffered more than the Burmese, because of the presence of two wedges (near Quetta and Dera Ismail Khan) of the Peninsula distorting the smoothness of the arc.

The thrust phenomena around the tips of the Kashmir and Assam wedges are interesting. In the former, the formations almost turn a full circle over to the west and south-west, the thrusts being directed everywhere at right angles to the strike of the rocks. The rocks have literally ' flowed ' around the tips of the wedges and the direction of flow is anti-clockwise in the Kashmir wedge and clockwise in the Assam wedge, as pointed out by Du Toit (1937, p. 184).

Our knowledge of the geology and the details of the structure of the Himalayas and associated mountain ranges is still very meagre. The area is large and inaccessible and it will be many years before even

parts of the gaps in our knowledge are filled up. Wadia has remarked 1938, p. 117) :—

> "The plan of the great edifice of the Himalayas is discernible only in the haziest outline yet. We cannot be so bold as to say that the Himalayas are built on the plan of the Alps, nor even that their architecture is individual. No doubt several tectonic features are common and the Alpine-Himalayan axis of earth-folding originated in one common and continuous impulse. But the proportions are so vastly different...........the one may be like an ornately built, delicately chiselled chapel, and the other a huge sun-altar of rough-hewn blocks".

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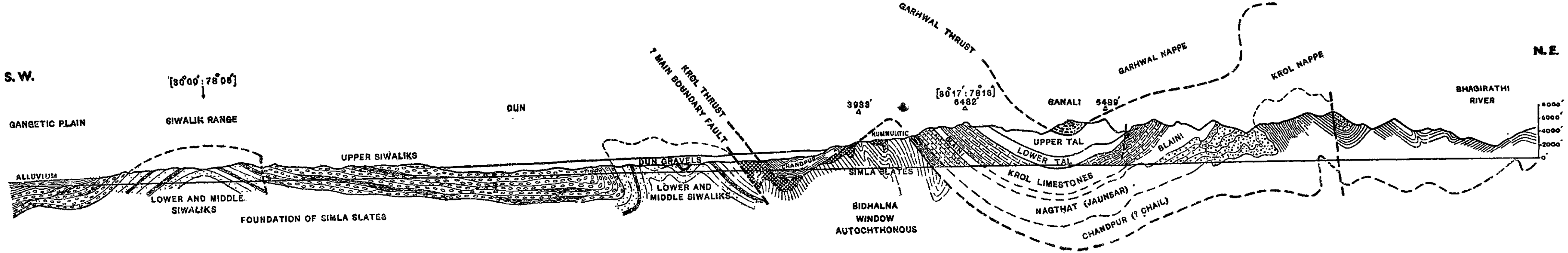
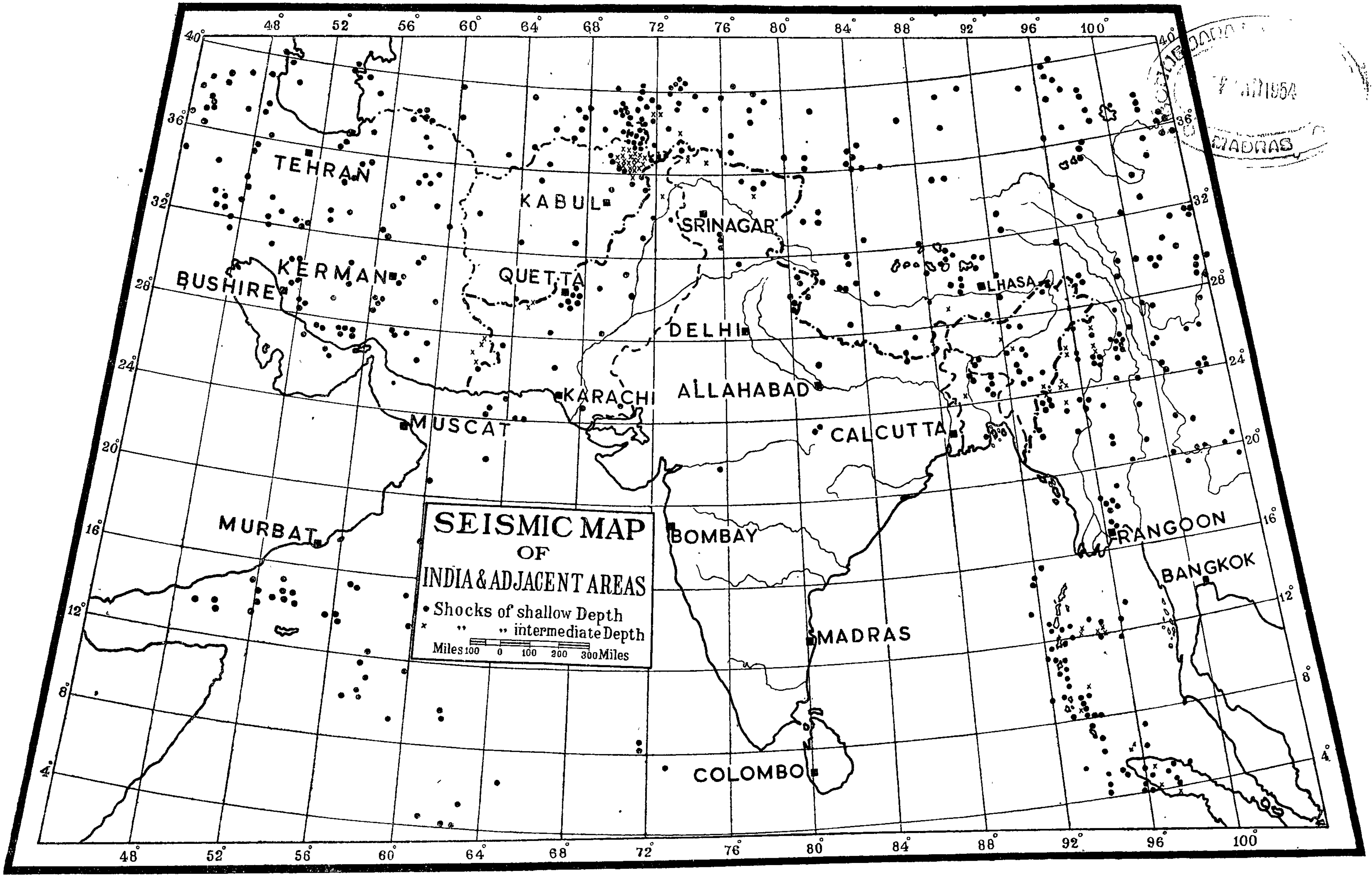
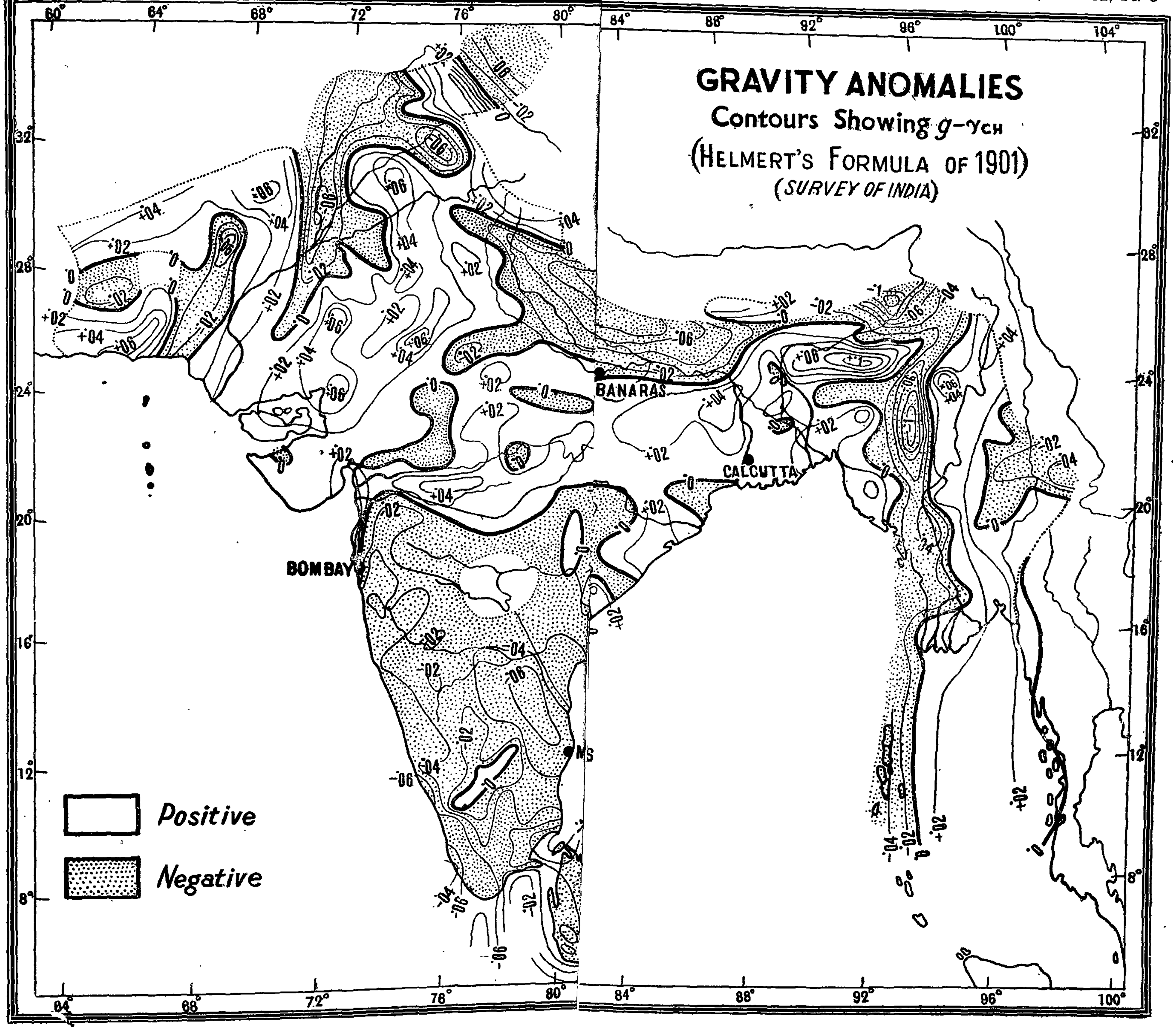


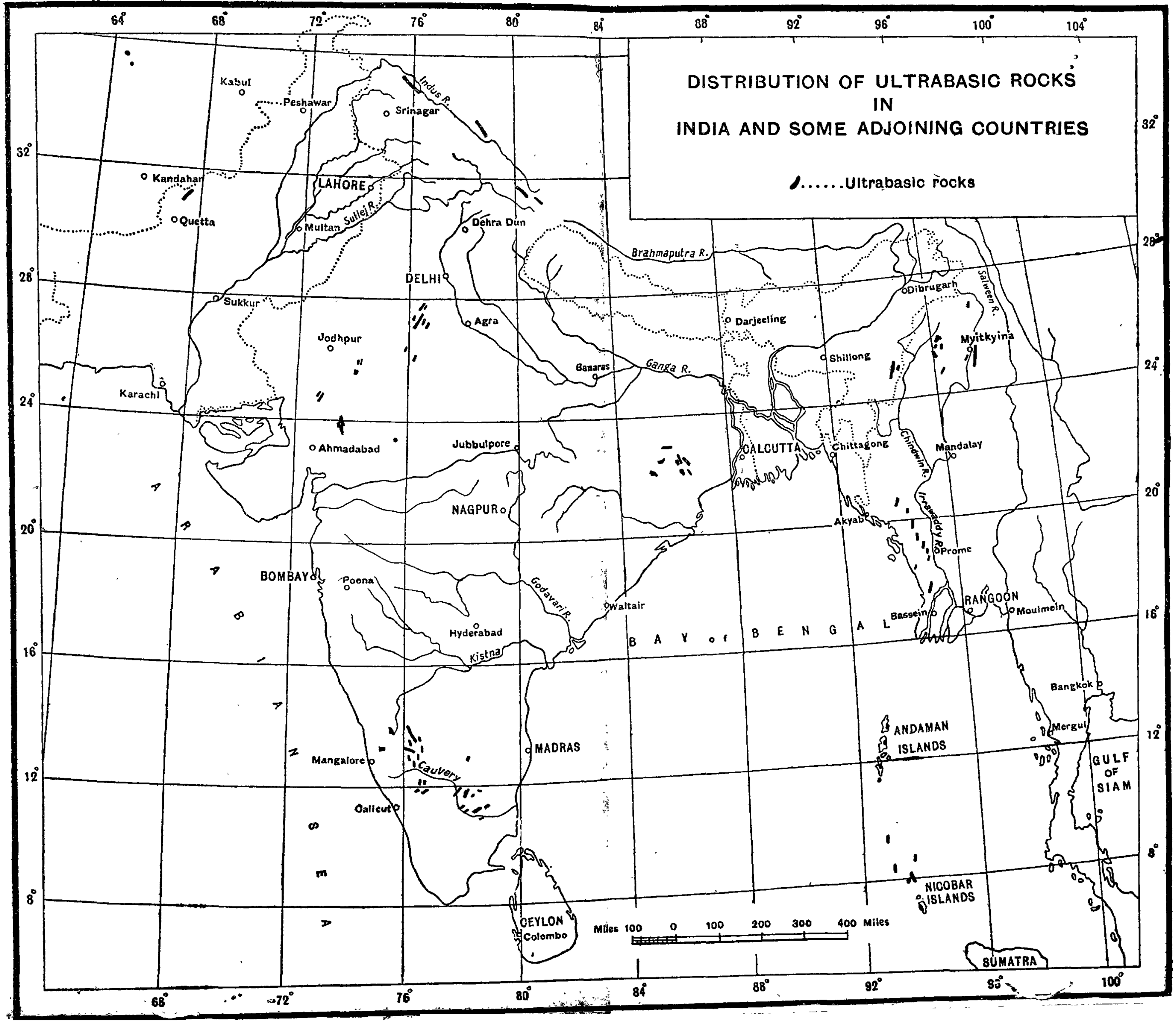
SECTION ACROSS THE GARHWAL HIMALAYAS.

(After J. B. Auden, 1937)


SEISMIC MAP
OF
INDIA & ADJACENT AREAS
• Shocks of shallow Depth
× " " intermediate Depth
Miles 100 0 100 200 300 Miles
TEHRAN
KABUL
SRINAGAR
KERMAN
QUETTA
BUSHIRE
LHASA
DELHI
KARACHI
ALLAHABAD
MUSCAT
CALCUTTA
MURBAT
BOMBAY
RANGOON
BANGKOK
MADRAS
COLOMBO

MADRAS 1954


GRAVITY ANOMALIES
Contours Showing $g-\gamma_{CH}$
(HELMERT'S FORMULA OF 1901)
(SURVEY OF INDIA)
BANARAS
CALCUTTA
BOMBAY
Positive
Negative


DISTRIBUTION OF ULTRABASIC ROCKS
IN
INDIA AND SOME ADJOINING COUNTRIES
......Ultrabasic rocks
Kabul
Peshawar
Srinagar
Indus R.
Kandahar
Quetta
LAHORE
Multan
Sutlej R.
Dehra Dun
DELHI
Brahmaputra R.
Sukkur
Agra
Darjeeling
Dibrugarh
Salween R.
Jodhpur
Myitkyina
Shillong
Banaras
Ganga R.
Karachi
Ahmadabad
Jubbulpore
CALCUTTA
Chittagong
Chindwin R.
Mandalay
NAGPUR
Akyab
Irrawaddy R.
Prome
BOMBAY
Poona
Godavari R.
Waltair
RANGOON
Moulmein
Bassein
Hyderabad
Kistna
BAY of BENGAL
ARABIAN SEA
Bangkok
ANDAMAN ISLANDS
Mergui
Mangalore
Cauvery
MADRAS
GULF OF SIAM
Calicut
NICOBAR ISLANDS
CEYLON
Colombo
Miles 100 0 100 200 300 400 Miles
SUMATRA